SUB-STATION PRACTICE

By the same Author

ELECTRIC POWER STATIONS
(Two Volumes)

SUB-STATION PRACTICE

By

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PREFACE TO THE SECOND EDITION

THE need for this edition has afforded an opportunity of including further information and illustrations throughout the text which, I feel, will enhance the value of the work. The continued growth of electric power supply systems has necessitated the provision of many additional sub-stations in order to meet the demand. No radical changes have been made either in sub-stations or their equipment since the first edition, but considerable experience has been gained in respect of applications of sub-station equipment. Since the first edition, the supply industry in this country has been placed under national ownership and greater opportunities now exist for the pooling and dissemination of experience and knowledge which should ultimately lead to technical and economic improvements.

T. H. CARR

BRADFORD.
1952

PREFACE TO THE FIRST EDITION

THE end to electrical development is not yet in sight, and in the years immediately ahead of us the rate of growth of power supply is likely to surpass all expectations.

The progress of the electricity supply industry has been marked by a series of far-reaching events, of which the " Grid " System has undoubtedly proved to be one of the most important.

> " Then for miles the only signs of progress are the pylons taking great swinging strides over the countryside. There they go, these rigid lanterns, lightless yet giving light, festooned with bells that never ring—signs of progress, modern symbols of fertility . . ." (Hugh Massingham—*The Harp and the Oak*.)

There are many excellent books and papers dealing with Switchgear, Transformers and Converting Plant. This is not surprising in view of their importance and the part which they play in the transmission and distribution of electrical energy.

Few books, however, deal with sub-station design, construction and operation.

It is hoped that this volume will prove useful to mains and substations engineers, consulting engineers, junior engineers, operatives and students.

The author wishes to thank the many firms who have supplied information and illustrations.

Acknowledgment is also made to the vast field of engineering literature which has been consulted, and to which reference is made in the bibliographies.

Finally, his best thanks are due to Messrs. N. London and C. Brooke for their assistance by way of typing and preparation of final tracings.

T. H. CARR

BRADFORD.
1946.

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CHAPTER I

GENERAL CONSIDERATIONS

Introduction. The distribution of electrical energy generated in major power stations is being spread over larger areas, with the result that greater demands have to be met in these areas. In view of the magnitude and importance of transmission and distribution networks, reliability and efficiency are the first essentials, with reasonable allowance for economic considerations. Practice indicates that even the most trivial causes may result in serious disturbances with consequent loss of continuity of service.

Electricity should be generated and distributed having full regard to reliability, efficiency and economy. Every new piece of equipment and plant necessitates an increased capital investment which in turn increases the capital or fixed charges. To balance such an expenditure it is necessary to see that revenues rise at least as rapidly as fixed charges, and preferably faster. Much time and thought have been devoted to the reduction of the cost of sub-station buildings and equipment, with the object of affording an economical supply to all classes of smaller consumers. The revenue obtained from such supplies is usually comparatively small, with the result that the capital outlay permissible to the supply authority is necessarily limited. The supplies given to rural districts are but typical of the financial risks which the supply authority may have to cater for, and in order to lessen such risks it may be necessary to include certain clauses in the supply agreements. Some such clauses are :

(1) The cost of L.V. or M.V. service lines to be borne by the consumer.

(2) A minimum annual revenue to be guaranteed for a number of years, *e.g.*, say five years at 20 per cent. of the cost borne by the supply authority.

(3) Consumer to make a contribution of the difference between the total cost and the cost borne by the supply authority.

(4) Wayleaves to be granted for all poles and equipment installed on the property supplied, including transfer of land required for substations at the valuation of the district valuer.

(5) Consumer to undertake to give consents and facilities necessary to enable supply authority to afford supplies to adjacent premises.

When planning distribution systems, including sub-stations, the following should always be kept in mind :

(a) Reliability of supply.
(b) Conservation of materials.
(c) Safety of personnel and equipment.
(d) Minimum outage from malicious interference.
(e) Simple equipment—to install, operate and maintain.

In achieving the desired results due regard should be given to : probable total plant load ; ideal unit load area size ; division of total plant into economical unit load areas ; form distribution system taken together with full details of distribution circuits.

The cheapening of the sub-station, and especially its equipment, while being possible, should not in any way impair reliability of supply, otherwise a temporary saving in capital cost may be obtained only at the expense of a subsequent considerable loss of revenue from other consumers. The growth of load on power supply networks has given new emphasis to the problems of ensuring continuity of supply under almost all conditions, including aerial bombardment.

Maximum reliability of generating plant and distribution equipment are not the only items requiring attention, for means have to be implemented to facilitate normal inspection and maintenance and without the necessity of temporarily interrupting the supply. These considerations have in consequence played an important part in the selection and layout of distribution equipment. A careful study of the high-voltage distribution network and the loadings obtaining will enable major developments to be estimated with reasonable accuracy for a number of years ahead. It will be appreciated that much will depend on the area served, and before deciding on any particular scheme it is advisable to be acquainted with all existing and potential loads within the area. Full particulars of industrial, commercial, agricultural and domestic areas, including private concerns, all require careful consideration when planning ahead. In some areas co-operation with colliery companies is sometimes possible and mutually beneficial.

With the continued rapid development of electricity supply, substations play a very important part. In some undertakings the

domestic load has increased with such rapidity that it has been necessary to make special provisions for dealing with it. ~~The sub-station is~~ the interconnecting link between the power station and the consumer. Sub-stations are necessary because it is economical to transmit electrical power over appreciable distances at high voltages, whereas it can only be economically utilised at comparatively low voltages. The voltage chosen depends primarily on the load to be given and distance from the power station, but a compromise has to be made between the costs for heavy current and the costs for high voltage. By virtue of economic necessity many of the present-day systems have been built up piecemeal, commencing with single supplies from the power station, ultimately developing into ring mains or duplicate supplies as the load has grown. The original systems were chiefly 6·6 kV and 11 kV, but the present tendency is to supply all primary sub-stations at 33 kV and transform to 11 kV or as may be required. This may necessitate the installation of either transforming or converting plant at or near the area served. The incoming and outgoing supplies of this plant must be controlled, and therefore entails the use of some form of switch or fuse gear. The transforming and/or converting plant and switchgear have to be accommodated, and the sub-station becomes an established fact. Sub-station design is, therefore, the selecting, arranging and housing of this plant in accordance with the best present-day practice.

The arrangement of buildings, supporting structures and enclosures will primarily depend on the plant to be installed, but in many cases site conditions alone will be the deciding factor. The scarcity of land in industrial areas and works sometimes leads to the origin of specially arranged sub-stations, particularly where transforming or converting plant of the order of 5,000 to 15,000 kVA is required. Static transforming stations of 60,000 kVA and above are, of course, quite common in the grid system, and special layouts have been devised and put into satisfactory operation.

It seldom happens that one sub-station is like any other in every respect, consequently different problems present themselves in the design of each new station. Although the design and layout are straightforward in every way, it is necessary that the designer should be fully acquainted with the plant to be installed and so obtain the most economical layout of plant consistent with those all important factors—safety and reliability. The alternatives to the use of many general supply sub-stations are larger M.V. cables or higher voltages

at the consumers' service points. The former is not favoured, and for the latter to be a practicable proposition for many consumers sub-stations would be necessary.

The importance of sub-station design, construction, operation and maintenance is apt to be underrated on account of its apparent simplicity, but where a systematic attempt is made to arrive at the ideal it is surprising how complex the problem sometimes becomes. The many possibilities of layout and arrangement provide much scope, but the final choice should form a well-made link in the system of which it is part. So far as the architectural features are concerned, every endeavour should be made to keep them in line with surrounding buildings, but under no circumstances should the essential principles be forfeited to attain this end.

The plant contained in a sub-station consists of four main items :

1) Higher voltage switchgear controlling the incoming supply.
2) Transformers, convertors and rectifiers.
3) Lower voltage switchgear controlling the outgoing supply.
4) Cables and auxiliary apparatus.

There are many ways in which these items of plant may be arranged in relation to one another, and the designer should reduce the subject to an economical association of essential principles.

In considering sub-station design it is necessary to know the behaviour under normal and abnormal conditions of the various items of plant to be installed. Experience only has given us this knowledge to which the developments in the design of many present-day sub-stations are due. The fault in the design of many existing sub-stations is that they take no account of the behaviour of the plant under fault conditions, and the sole object appears to have been to install the maximum amount of plant in the minimum amount of space. There are many instances where conditions obtaining during the growth of undertakings have made it almost impossible to proceed along approved lines.

Growth at the rate of 10 per cent. per annum means almost a doubling of system capacity, and in particular of the number of sub-stations, every seven years ; this rate of growth is quite reasonable in normal times.

Principles of Design. What to-day are considered to be the essential principles of sub-station design may be outlined in order of their importance :

(1) Safety and reliability of supply from sub-station.
(2) Minimum operating and maintenance costs.
(3) Minimum of capital cost.

The designers' share in ensuring these requirements is an arrangement and choice of plant and building which meets the following specification :

(*a*) The plant should be of sound design and construction so that breakdown is infrequent.

(*b*) The automatic protective devices should rapidly remove faulty apparatus from the system without interference to healthy plant.

(*c*) The layout of plant should be such that breakdown of faulty gear should not damage or adversely affect the operation of the sound plant, the building or any persons employed therein. Separation of transformers by fireproof partitions or barriers from each other and from switchgear is desirable, for it reduces consequential damage to a minimum. The wiring and methods of leading-in cables should be as simple as possible.

(*d*) The arrangement and accommodation should allow the plant to perform its duties efficiently, whilst its operation should be simple, reliable and foolproof. Suitable means of access and handling for the plant should be provided.

(*e*) Adequate ventilation to each transformer and converting plant chamber is essential to extract the heat from the transformer or machine losses, and so obtain maximum output for a given maximum temperature. Switch chambers should be well ventilated to prevent sweating, and provision made for escape of high air pressures or blast. Artificial heating may be used. All open-

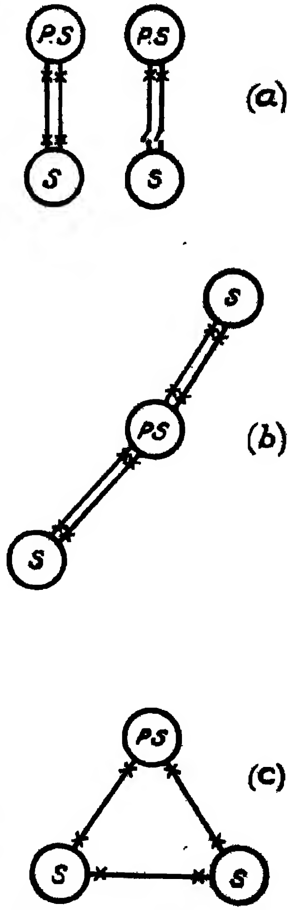


FIG. 1. Systems of supply to primary sub-stations.

ings should be arranged to prevent the ingress of rain, snow, birds or vermin.

(*f*) Maintenance and repairs to plant and buildings should be possible (with safety to persons employed and to the rest of the plant and buildings) without affecting the service. Unless conditions permit of plant being completely shut down when work thereon is necessary, effective sub-division into units or sections is essential.

(*g*) The plant and buildings should not be damaged or adversely affected by climatic conditions, flood or fire.

(*h*) Extensions to either plant or buildings should be possible without affecting the service, the existing plant and the safe operation of the sub-station. Space should be allowed in the initial building for a reasonable addition of plant to meet future demands.

(*i*) A reserve of plant should be maintained in readiness to meet emergency conditions.

(*j*) The building and enclosure should be of adequate proportions, bearing in mind the cost of land, building work, cabling, etc.

The principles enumerated cannot always be met completely, for in practice it is usually found that absolute perfection is rarely justified economically. It should always be borne in mind that the effect of a sub-station failure upon the high voltage distribution systems is of much more importance than the effect on the particular service from that sub-station. If sub-station plant should fail, the damage and the interruption to service should be confined to that sub-station. Apart from the engineering requirements, the design of sub-stations is affected by the policy adopted on the supply system with which they are associated. The ever desirable factor of reliability of supply plays an important part, and in no small way may result in considerable expense being incurred in the design and construction of sub-stations with the object of minimising failure of supply.

In general, sub-stations can be considered as switching or control centres for the higher voltage transmission systems and distribution networks.

Sub-station design cannot be treated on a minimum cost basis if the future requirements of a supply system are to be catered for even within reasonable limits of growth ; also to be considered are the increasing possibilities of interruption of supply due to original curtailments of stand-by plant, sectionalising and perhaps protective apparatus. The sub-station is an engineering job first and foremost,

and should not take second place to the buildings from architectural or any other points of view.

Compared with the complete plant installed the cost of the building is comparatively small, probably varying on the average from 15 to 25 per cent., Tables 1. 2 and 3, and the difference between two buildings expressed as a percentage of the total cost is very small.

TABLE 1. *Sub-station Plant and Building Costs*

Station	Costs Pre-1940		Plant cost per cent. of total cost	Remarks
	Plant £	Buildings £		
A	6,800	1,350	83·5	6·6 kV/400-volt switchgear and transformers.
B	9,500	3,000	76·0	Switchgear, transformers and traction rectifiers.
C	3,500	1,200	74·5	Switchgear and transformers.
D	5,800	2,700	68·0	Switchgear, transformers and traction rectifiers.
E	86,000	20,000	81·6	33 kV switch houses only.

A trolley-bus sub-station built and equipped during 1948 cost some £10,100, made up as follows :

	£
2 -350 kW M.A. glass-bulb rectifiers	3,700
6·6 kV switchgear	3,700
Building	2,700
Total .	£10,100

The cost of a tapping from a 33 kV overhead line to provide a 11 kV supply (1949) was approximately as follows :

	£
2—33 kV isolators	540
1—33 kV isolator and fuse for transformer . .	800
1—33/11kV transformer including tap changing equipment (1,000 kVA)	3,000
Building for tap changing equipment	750
This includes the 11 kV O.C.B. Total .	£5,090

TABLE 2. *Sub-station Costs*

Station	Land £	Buildings £	Switchgear £	H V cabling £	Transformers £	Rotary convertors and rectifiers £	Traction switch gear £	M V Distribution Boards £	Battery £	Fire-fighting £	Telephone £	Other equipment £	Plant cost per cent	Total £	Remarks (Pre-1940)
a	36	835	1,184	110	1,190	—	—	300	20	—	7	20	76	3,702	2–1,000 kVA O/D transformers 250 M.V.A., 6·6 kV M.C. switchgear 12 way M.V. dis board
b	—	1,350	3,507	85	1,260	—	—	355	25	—	5	5	80	6,592	2–11,000 kVA O/D transformers 250 M.V.A., 6·6 kV M.C. switchgear 12 way M.V. dis board
c	81	774	160*	50	—	3,370	—	—	—	5	5	18	80	4,463	*Modified 6·6 kV switchgear 2–230 kW G.B. rectifiers
d	127	753	2,753	52	810	—	—	322	28	—	5	—	82	4,850	2–750 kVA O.D. transformers 250 M.V.A. 6·6 kV M.C. switchgear 12-way M.V. dis board
e	368	7,400	10,815	1,205	4,177	3,724RC 2,567R	3,920	810	25	—	5	190	78	34,206	2–500 kVA O/D transformers 1–500 kW rotary convertor 1–500 kW G.B. rectifier
f	264	12,020	20,676* 10,226†	3,370	14,560	3,260RC 3,248R	4,230	260	1,114	1,600	7	170	83	75,005	3–7 500 kVA O/D transformers *750 M.V.A., 33 kV M.C. switchgear †250 M.V.A., 6·6 kV M.C. switchgear 2–500 kW rotary convertors 1–710 kW S.T. rectifier

TABLE 3. *Sub-station Costs*

Type	Plant	Relative Cost
Pole	50 kVA transformer pull-down switch fuses. M.D.I. Box . . .	1·0
Underground	150 kVA transformer pits, ring main isolator	2·6
Raft	200 kVA transformer O.C. breaker, R.C. raft	3·0
Kiosk	200 kVA transformer, kiosk, fusegear, ring main isolator . . .	4·0
Brick	200 kVA transformer, building, fuse-gear, 3 O.C. breakers . . .	10·0

Speaking generally, sub-station buildings can be considered entirely on their engineering merits providing care is taken to guard against the provision of redundant building space, but always keeping in mind the future requirements of the area served.

The provision of spare plant involves the sub-division of equipment into as near as possible similar sections so proportioned that in the event of failure of one section there will be adequate plant left to deal with the electrical load. The first problem is the number of sections to be installed for a given load, assuming one as reserve, and in practice two is the usual number for all but very large sub-stations.

For a 1,000 kVA load two transformers, each of 1,000 kVA, are cheaper than three 500 kVA, whilst two 100 kVA transformers are cheaper than three 50 kVA units. Further, the total cost of switchgear will be greater with an increased number of transformers, in addition to the larger site area and building required. Perhaps two of the most important requirements in the layout and arrangement of a sub-station

are protection from ~~consequential~~ damage and ease of inspection and maintenance. These requirements are almost identical in their effect on the problem, since to a great extent arrangements made to prevent consequential damage also minimise accidents to personnel and plant during inspection and maintenance. Consequential damage is inferred

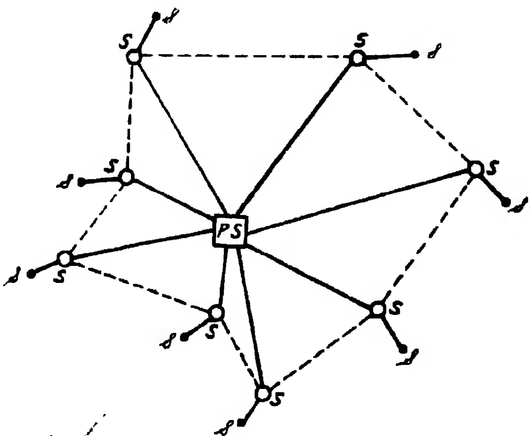


FIG. 2. Radial feeder with ring mains.

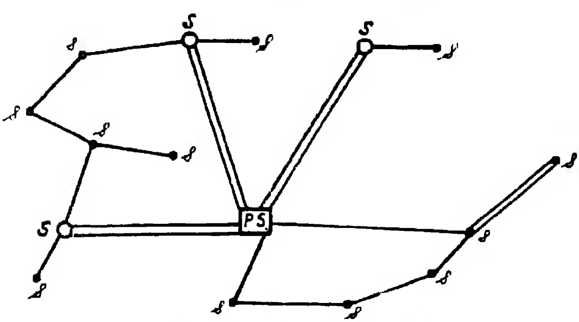


FIG. 3. Alternative layout with duplicate feeders to primary sub-stations.

to be the damage to any part of the plant caused by breakdown of equipment in another section. Protection from consequential damage entails the provision of fire and explosion proof screens, and generally the most convenient form of fireproof screen is brickwork, preferably of blue bricks. Within recent years considerable thought has been given to the possibility of attack by enemy aircraft, and in this respect

precautions have been taken to deal with blast and splinters from bombs bursting in the vicinity. Probably the inclusion of a number of key underground sub-stations on a system would help to solve difficulties which may arise in such circumstances. Much experience has been gained in this respect, out it is to be hoped that future generations will be free from such considerations.

Before a sub-station can be planned it is necessary to fix the number and type of units it is likely to accommodate to meet an anticipated load keeping in mind the need for a reasonable margin of spare plant to cover emergency conditions. Summarising, it may be said that the following apply to the majority of sub-stations:

(1) Sub-station plant should wherever possible only be installed as required.

(2) The capital cost of the plant should at all times be economical in relation to the loads to be met.

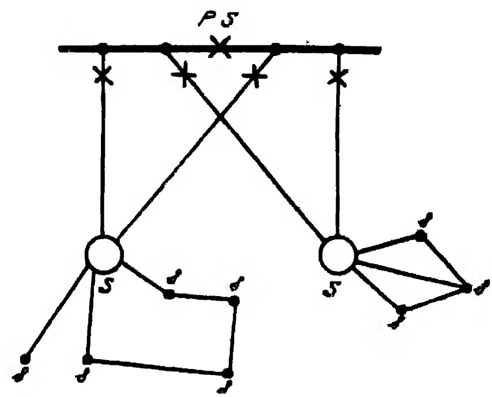


FIG. 4. Supply Systems.
S-Primary Sub-station. s—Secondary Sub-station.

(3) Faulty plant should not affect sound units and the sub-station should always be capable of operating at reduced output.

(4) Plant should be arranged to operate at maximum efficiency by automatically, or otherwise, controlling the units on load in accordance with the loads to be met.

(5) Facilities should be provided to enable maintenance and inspection to be carried out during light load periods.

(6) Sub-division by some unit system facilitates interchangeability.

Statutory Requirements and Definitions. As the majority of substations come under the Home Office Regulations for Factories and Workshops and the Electricity Supply Regulations, these should be carefully perused, for intelligent interpretation is most essential. Readers abroad will no doubt find that the Codes or Regulations of their own countries will vary to some extent in details, but the principles will generally apply.

" Sub-station " means any premises or enclosure or part thereof being large enough to admit the entrance of a person after the apparatus is in position, containing apparatus for transforming or converting energy to or from voltage above medium voltage, other than transforming or converting solely for the operation of switchgear or instruments, with or without any other apparatus for switching, controlling or otherwise regulating the energy, and includes the apparatus therein.

" Outdoor Sub-station " means any ground or place where apparatus of the kind included within the definition of sub-station is situate in the open air, and includes the said apparatus.

" Low Voltage " means voltage not exceeding 250 volts under normal conditions, subject, however, to the percentage variation allowed.

" Medium Voltage " means a voltage exceeding 250 volts but not exceeding 650 volts under normal conditions, subject to the percentage variation allowed.

" High Voltage " means a voltage normally exceeding 650 volts but not exceeding 3,000 volts.

" Extra-high Voltage " means a voltage normally exceeding 3,000 volts.

" Consumer " means any body or person supplied or entitled to be supplied with energy by the undertakers.

" Authorised Person " means (*a*) the occupier, or (*b*) a contractor for the time being under contract with the occupier, or (*c*) a person employed, appointed or selected by the occupier, or by a contractor as aforesaid to carry out certain duties incidental to the generation, transformation, distribution or use of electrical energy, such occupier, contractor or person being a person who is competent for the purposes of the Regulation in which the term is used.

The Factory and Workshop Acts, 1901–29, comprise thirty-two Regulations relating to electrical equipment, all of which may apply to sub-station practice. Those worthy of special consideration are Regulations 30 to 32 inclusive, whilst Regulations 14 to 19, also 25 and 27, have a direct bearing on sub-station work. (See Fourth Edition, 1951.)

A structure in order to qualify for the title of sub-station must be premises large enough to admit a person when all the necessary apparatus is in position. Although this is a generally accepted idea, sight should not be lost of the explanatory memor-

andum dealing with "Electrical Stations" which runs as follows:

"'Electrical Stations', that is to say, any premises or that part of any premises in which electrical energy is generated or transformed for the purpose of supply by way of trade or for the lighting of any street, public place or public building, or of any hotel or of any railway, mine or other industrial undertaking."

Section 103 of the Factories Act, 1937, also covers electrical stations. These bring in almost every electrical distribution structure to which exemption is not specifically given.

When planning sub-stations and distribution centres it is desirable to take note of all safety regulations which exist. The question as to whether any particular premises are or are not within any particular regulation should not carry "weight", for safety to human life is of prime importance. Regulations are not made to protect workers against their own errors or maybe their own folly. Employer defendants sometimes contend that an accident is caused or contributed to by a plaintiff's own negligence and breach of statutory duty in failing to take proper precautions for his own safety. The simple facts of a case have to establish a good action in common law of failure by his employers to do their duty to him. The statutory regulations lay it down as the duty of workmen to conduct their work in accordance with those regulations. The plaintiff is not obliged to rely on a break of statutory obligation at all. As far as sub-station operation and maintenance are concerned, the switching of apparatus under load conditions presents an element of risk to both the safety of the operator and the maintenance of supply. The provision of remote-controlled equipment, interlocking devices and visual and audible indicators has done much to reduce such dangers, but the human element still remains a vital factor. The presence of more than one authorised person when it is necessary to carry out work on live higher-voltage equipment also

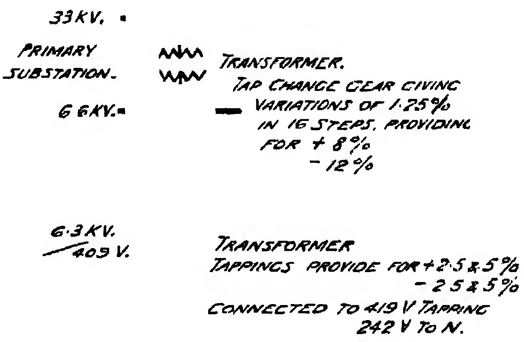


FIG. 5. Voltage Regulation.

tends towards the elimination of such dangers, but even then accidents still occur. Reliance has to be placed on technical knowledge, mental concentration, and careful observance of every possible precaution when work of this nature has to be done. The requirement that all apparatus shall be so worked as to prevent danger, puts responsibility on the workman.

Section 113 (Factories Act, 1937) as amended by the 1948 Act, requires that not less than one month before occupation of a sub-station coming within Section 103 of the same Act, i.e. in general attended sub-stations, written notice shall be given to the factory inspector of the district. The Electricity Supply Regulations, 1937, Regulation 30 (*d*) states that the undertakers shall give to the factory inspector of the district concerned notice of their intention to commence a supply of energy at high voltage to any premises to which the Home Office Regulations (Electricity (Factories Act) Special Regulations, 1908 and 1944), apply.

In sub-stations where there is separate ownership of plant and apparatus and joint access is permissible to the undertaker and the consumer the question may arise as to who is the occupier. In such cases it is generally considered that the owner or lessee of the transforming and converting plant is the occupier of the station and is responsible for carrying out all obligations under the regulations, including the notification of dangerous occurrences, even though such occurrences take place on apparatus in the station which is not his property.

The occupier of any sub-station to which the regulations apply must display in conspicuous and easily accessible locations the following notices :

Attended sub-stations :

Form No. 2.—Abstract of Factory and Workshop Acts (Non-Textile Factories).

Form No. 37A.—General Register of Young Persons, Accidents, Lime Washing, etc.

Form No. 60.—Lime Washing exemption.

Form No. 84.—Summary of Workmen's Compensation Act.

Form No. 85.—Accident Book; Workmen's Compensation Act, 1925.

Form No. 954.—Electricity Regulations.

Placard describing Treatment in case of Electric Shock.

In addition, a First Aid Box, together with Form No. 923, must be provided and conspicuously located.

Non-attended sub-stations :

Forms No. 2, 84 and 954.

Placard describing Treatment in case of Electric Shock.

In the smaller sub-stations, where full display is impracticable, a notice may be exhibited stating where the forms may be inspected, but it is essential that the " Shock " placard be displayed.

It should be remembered that responsibility for the observance of the regulations is not confined to the occupier. All persons engaged on electrical work in places where the regulations apply should be fully aware of the obligations imposed on them.

Sub-stations for Coal Mines :

All sub-stations for such service should comply with the Coal Mines General Regulations. The regulations concerning electrical personnel and equipment, etc., are Nos. 117 to 137 inclusive.

In Regulation No. 118 definitions are outlined, while Regulation No. 119 gives the notices which are to be sent to the inspector of the division.

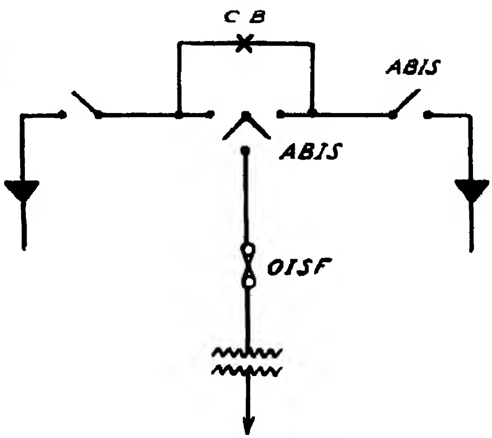


FIG. 6. Ring main unit.

A proper plan (Regulation 120), on the same scale as that kept at the mine in fulfilment of the requirements of the Act, shall be kept in the office at the mine, showing the position of all fixed apparatus in the mine, other than cables, telephones and signalling apparatus. The said plan shall be corrected as often as may be necessary to keep it reasonably up to date, and it shall be produced to an inspector of mines at any time on his request.

The following notices (Regulation 121), constructed of durable material, shall be exhibited where necessary :

(i) A notice prohibiting any person other than an authorised person from handling, or interfering with apparatus.

(ii) A notice containing directions as to procedure in case of fire.

This notice shall be exhibited in every place containing apparatus other than cables, telephones and signalling apparatus.

(iii) A notice containing directions as to the restoration of persons suffering from the effects of electric shock.

(iv) A notice containing instructions how to communicate with the person appointed under Regulation 128 (A). This notice shall be exhibited at the shaft bottom.

Where necessary (Regulation 123) to prevent danger or mechanical damage, switchgear, transformers, etc., shall be placed in a separate room, compartment or box of fireproof construction. Such apparatus should be housed apart, or at least placed in a recess.

Forms Nos. 11, 15B, 2264 and 318 ; and Circulars Nos. 31 and 23 should also be perused.

The Electricity Regulations for Quarries and similar regulations for metalliferous mines became operative in 1938 although a period of seven years was allowed to bring existing equipment into line with these new requirements. S. R. & O. 1945—Nos. 1350 and 1351 should be referred to for the present needs of the Minister of Fuel and Power.

Sub-stations for Cinematographs :

The State Regulation and Orders Nos. 983, 403 and 361, and Cinematograph Act, 1909, outline the general requirements for sub-stations in cinematograph premises. The Cinematograph Regulations, 1950, should be studied and the following extracts relate to the sub-station plant : Regulation 20 (*a*). The following plant and apparatus shall be placed in a separate enclosure or enclosures which shall not communicate directly with the auditorium or with any exit therefrom to the outside of the building, shall be so constructed as to prevent the spread of fire from within to the rest of the premises, and shall not be accessible to the public :

(i) Plant for the generation of electrical energy driven by steam, gas or oil engines, or other prime movers.

(ii) Main supply or main circuit transformers.

(*b*) Main supply and main circuit switchgear and fuses shall be placed in an enclosure, the door of which shall, if the enclosure communicates with any part of the premises to which the public are admitted, be kept locked.

Regulation 21 (*a*). Plant or apparatus specified in paragraph (*a*) or (*b*) of the last foregoing regulation shall not be installed, stored, or within the projection room.

The following notes may serve as a guide to such sub-stations, but were tabulated before the 1950 Regulations :

(*a*) The maximum fault energy permissible at the high voltage busbars shall not exceed 50 M.V.A.

(*b*) The voltage of supply shall not exceed 11 kV.

(*c*) The margin between this maximum high voltage fault energy and the rupturing capacity of the high voltage switchgear installed shall not be less than 25 per cent. The figure of 60 M.V.A. is chosen as a reasonable maximum and as allowing a 25 per cent. margin corresponding to 75 M.V.A., which is a manufacturing standard rupturing capacity for switchgear.

(*d*) The total capacity of the transforming plant installed shall not exceed an aggregate of 1·5 M.V.A.

The aggregate transforming capacity of 1·5 M.V.A. is arrived at by allowing 3·5 per cent. transformer reactance giving 25 M.V.A. maximum fault energy at the medium-voltage busbars. This is well within the scope of high rupturing capacity fuses and circuit breakers at 400 volts.

(*e*) The maximum fault energy which can appear at the main medium-voltage busbars or at any point on the M.V. installation shall not, at any time, exceed 25 M.V.A.

In order to take care of the condition arising when a sub-station is installed just outside cinematograph premises, the maximum fault energy at the M.V. busbars has been limited to 25 M.V.A., the maximum figure for which fuses are at present manufactured.

(*f*) In cases where the chamber containing main transforming plant or high voltage switchgear is incorporated in the cinema building, the following conditions shall apply :

(1) There shall be no communication between the chamber and the cinema building, and access shall be directly from outside only.

(2) The walls shall be of brick not less than 13 in. thick, or of other approved construction of equivalent strength.

(3) Roofs and floors shall be of not less than 6 in. reinforced concrete or of other approved construction of equivalent strength.

(4) Adequate and direct ventilation to outside air shall be provided and maintained.

(5) A suitable form of fixed automatic fire-extinguishing installation shall be provided.

(6) Adequate precautions shall be taken either by the provision of suitable sumpage or other means to prevent the spread of any fire resulting from the ignition of the oil.

(*g*) Provided that the foregoing building conditions would be inapplicable where :

The main transforming plant or high voltage switchgear is not incorporated in the building and is screened, divided or separated from the cinema building to the satisfaction of the licensing authority.

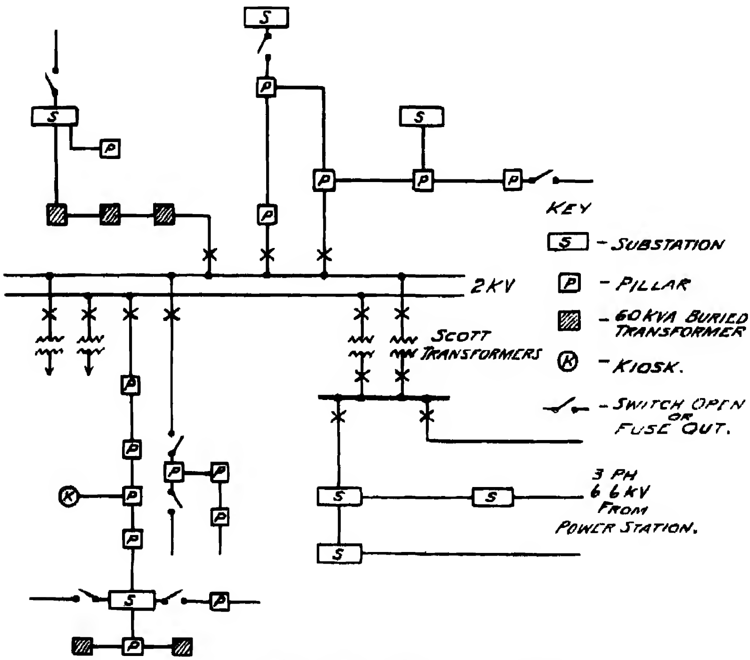


FIG. 7. Network supplied from sub-station.

Note. Any surplus capacity of transforming plant may be used for supply to outside consumers.

Choice and Location of Sites. The choice and location of sub-station sites are of prime importance in the planning of distribution systems. It is desirable that the sub-station sites should be as close as possible to the centre of gravity of the loads to be supplied. So far as industrial and commercial sub-stations are concerned, these will normally be placed on the premises of the consumer, usually without much difficulty.

The most troublesome of all is perhaps the selection of sites for the larger sub-stations, for the cost of land, nearness to residential property and potential use of a fairly large area of land must be considered. The difficulty of procuring the desired site may result in increased costs and impaired voltage regulation, and ultimately lead to the necessity for further sub-stations at a later date.

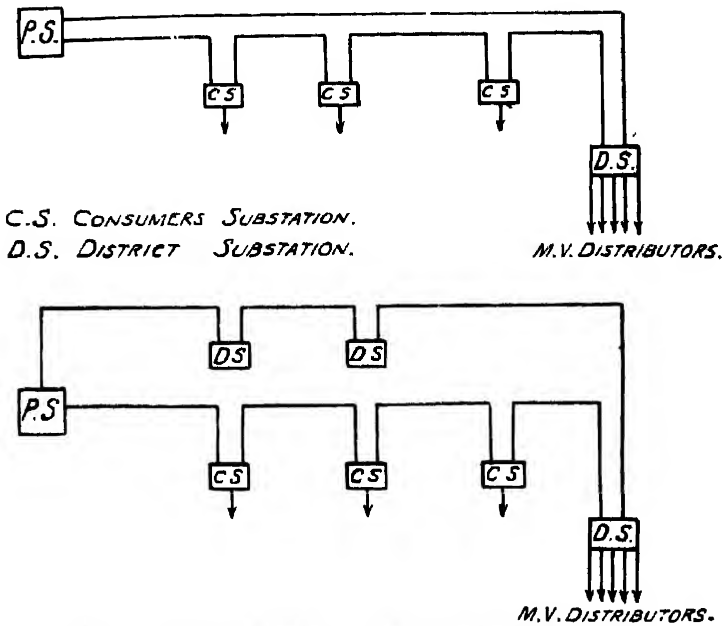


FIG. 8. Alternative feeder arrangements affecting sub-station connections.

Sub-stations should, wherever possible, be at ground level, as basements are liable to accidental flooding, fire-fighting may be impaired, and the installation and replacement of plant is more difficult and costly. If placed on higher floor levels, here again access is difficult and costly.

A far-sighted policy is essential in the selection of sub-station sites, and the requirements of the complete system should always be kept in mind, otherwise piecemeal additions will inevitably lead to an uneconomic distribution system. In urban and residential areas it may be preferable to purchase a dwelling-house which has sufficient adjoining land on which to erect a sub-station and let the house at a reasonable

rent. The position as regards sites in cities and industrial areas is becoming more difficult, and in some cases the underground and basement sub-stations are the only solution.

It is always advisable to keep in touch with local developments by way of the city engineer who can often be helpful in the location of sub-station sites. A typical letter may prove useful :

Electricity Sub-station Site,
Central Area.

Dear Sir,

A review of the existing loading conditions and probable future increase indicates that it will be necessary in the near future to establish a new sub-station in the centre of the city. A suitable location from our point of view would be in the area bounded by Throckley Street, Heddon Street, Pennyhill and Eastheddongate, as we understand that this area is scheduled for new planning, we should be obliged if you would investigate whether tentative provision could be made for a sub-station site of approximate size, 25ft. by 30 ft., excluding surround and approach road. Your reply will enable me to formulate draft technical schemes with a view to the development of a firm proposal for your consideration.

Land is both difficult to obtain and costly in the centre of a city, so that it may be necessary to give a supply from an outer area.

Location, appearance, reliability, ratings and arrangement of equipment, possible fire hazards and sound proofing are important. In certain American cities sub-stations with transformer capacities of 170 M.V.A. at 110 kV are in use.

Acquisition of Sites. The acquisition of sites is a problem of considerable importance in cities and towns, for there was much of the commercial element in such dealings until the passing of the Town and Country Planning Act of 1947. The sites for industrial sub-stations will offer few difficulties in this respect, for owners are usually desirous of affording full facilities.

The procedure to acquire land for sub-stations is laid down by Section 1 (1) of the Electric Lighting Act, 1909. The definition of the expression " generating station " given in the Electric Lighting Act, 1909, includes any station for generating, transforming, converting or distributing electricity. In the Electricity (Supply) Act, 1919, the expression " generating station " means any station for generating

electricity, including any buildings and plant used for the purpose, and the site thereof, and a site intended to be used for a generating station, but does not include any station for transforming, converting or distributing electricity. It is also provided in this Act that the Act shall be contained as one with the Electric Lighting Acts. The 1909 Act contemplates the purchase of land compulsorily for the erection of a station for transforming electricity, whereas the definition in the 1919 Act excludes any station for transforming.

Authorised undertakers can apply for Special Orders under Section 1 of the Electric Lighting Act, 1909, to authorise compulsory acquisition of land for the purpose of sub-stations and to receive the assistance conferred by the Public Works Facilities Act, 1930.

There are other Acts of Parliament which may affect the question of the acquisition of land for the purpose of the erection of buildings for use in connection with electricity undertakings, some of which are :

Land Clauses Consolidation Act, 1845.

Public Health Act, 1925.

Town and Country Planning Act, 1932.

Restriction of Ribbon Development Act, 1935.

The Roads Improvement Act, 1935.

Town and Country Planning Act, 1947.

The procedure is identical to that of acquiring a site for a power station. The requirements to be met in the compulsory acquisition of a sub-station site will be gathered from the following :

The Statutory Rules respecting applications for Special Order for compulsory acquisition of land provide (*inter alia*) as follows :

(1) Publication of notice by advertisement (allowing thirty days for objection).

(2) Service of notice of intended application upon

(*a*) the owner, lessee and occupier *of the land to be acquired* ; and

(*b*) the owners or lessees of *all lands or houses situate within* 300 *yards* of the land to be acquired.

(3) Printing of orders, notices, book of reference containing *names of owners, lessees and occupiers of the land to be acquired and of all lands and houses within* 300 *yards.*

(4) Large scale maps of the whole area of supply and of the land to be acquired.

(5) Payment of £40 (on deposit of documents) to cover ordinary expenses. Any additional expenses would be payable by the corporation or power company.

(6) Deposit with the appropriate authority of draft order, advertisements, books of reference, maps, and also with the clerk of the peace of the county.

(7) Formal compliance with the Acts and Rules to be proved by parliamentary agents.

It is probable that the total cost of obtaining a Special Order would be about £100, including the £40 mentioned, whilst the time taken to get it through would be anything up to six months, after which there would be arbitration as to price to be paid, and further delay accordingly.

A number of the former Statutory Undertakings have private Acts, and it is always necessary to refer to these.

Reference should be made to the Acquisition of Land (Authorisation Procedure) Act, 1946. Section 9 of the Electricity Act, 1947, provides that the above-mentioned Act shall apply to any purchase of land for any purpose in connection with the discharge of the functions of an Electricity Board.

Relation of Sub-station to Supply System. Before proceeding with a sub-station, it is appropriate to consider its relation to the electricity supply system as a whole.

The supply system embodies generation, transmission and distribution, and it is advisable to consider the effects which one or the other may have on the sub-stations which go to make up a system. This really amounts to a consideration of the planning of the higher voltage distribution networks and centres. To show the necessity for a thorough investigation a number of typical systems are given, from which it will be appreciated that varying electrical conditions exist all of which may affect sub-station design and operation. The fact that reliability of supply is of primary importance almost always implies that a duplicate supply is necessary in all primary and secondary sub-stations. This can usually be provided by one of the following methods :

(1) Parallel feeders.
(2) Ring main feeders.
(3) A combination of (1) and (2).

The choice between (1) and (2) is chiefly an economic one, and depends to a large extent on the physical position of the source of supply relative to the sub-stations under consideration.

For the purpose of illustrating the problems to be met, Figs. 1 to 4 will suffice. Where a single source of supply only is given to one main

sub-station, the obvious method of providing an alternative is the use of parallel feeders. With two sub-stations placed on opposite sides of the power station or bulk supply station, parallel feeders would also be used unless there was a possibility of another sub-station which would justify a ring main with a possible alternative feeder to it from the source of supply.

By using parallel feeders, the cost of cabling is less than with ring main feeders, although the total length would be about the same in each case. The size of the ring main feeders from the source of supply

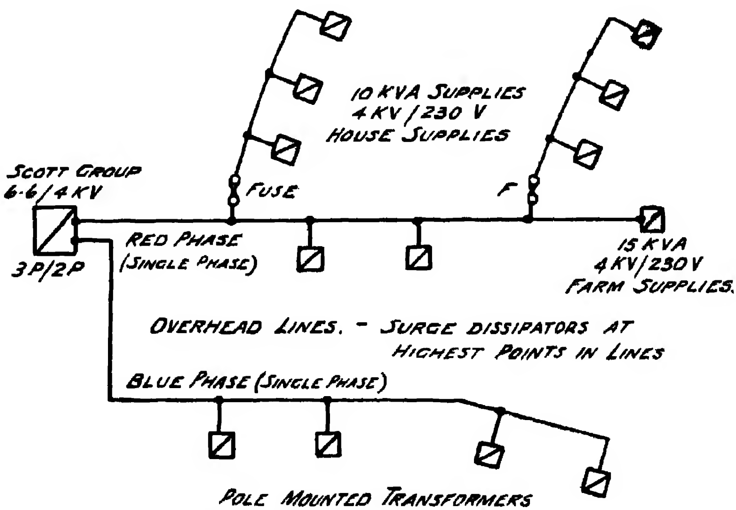


FIG. 9. Rural distribution network.

should normally be twice that of the parallel feeder cable if sub-stations are to maintain full output with one cable out of commission. The ring main system requires two circuit breakers at the power station against four with parallel feeders, and in large capacity stations the cost of switchgear may be comparatively high. The total length of cable required to be laid may be less, but the cost of laid cable does not vary directly with the current carrying capacity. The cost of excavating, laying and re-instating are independent of copper section.

Damage to cabling by enemy air attack has given added justification to the ring main system, since the alternative supply is by way of a different route. On the other hand, the parallel feeder system may be said to afford a greater degree of reliability of supply, since failure of

any one feeder would only deprive one single sub-station of its alternative supply. The same trouble on a ring main would result in loss of the alternative supply to all sub-stations.

Both lend themselves to the alternative supplies being taken from switchboards at the power station which are physically and electrically separated, but a supply can always be maintained to all primary sub-stations with parallel feeders.

Voltage regulation is not too good with a ring main, especially if one feed is out of service, but on-load tap changing equipment effects an improvement. Some typical system voltage drops are given :

Higher voltage distribution :

	Per cent.
11 kV voltage variation	5·0
11/3 kV transformer regulation	2·5
3 kV cable variation	2·0
3/0·4 kV transformer regulation	2·5
Total	12·0

Lower voltage distribution :

	Per cent.
11 kV voltage variation	5·0
11/0·4 kV transformer regulation	3·0
0·4/0·23 network and services variation . . .	4·0
Total	12·0

The transformers at the main sub-stations are assumed to have voltage regulating equipments to maintain the voltage on the busbars of the higher voltage system at a constant value. The statutory permissible voltage variation is ± 6 per cent., *i.e.*, 12 per cent. total (see Chapter X).

Supply to residential districts :	Percentage voltage drop
6·6 kV 3-phase feeder (4,000 yards—660 amps./in.^{2}) .	1·75
6·6 kV 3-phase/2–3 kV, single-phase transformer (2,000 kVA, load 1,500 kVA)	0·80
3 kV S.P. feeder (1,000 yards—600 amps./in.^{2}) . .	1·10
3 kV/460v., 230v. transformer (400 kVA, load 400 kVA)	1·10
L.V. distributors (500 yards—600 amps./in.^{2}) . .	4·00
(Allowing for mid-wire drop—unbalanced loads.)	
Total	8·75

	Percentage voltage drop
Supply to city districts :	
6·6 kV 3-phase feeder (4,000 yards—600 amps./in.^{2})	1·75
6·6 kV/400v., 230v. transformer (1,000 kVA, load 750 kVA)	2·50
L.V. distributors (500 yards—100 amps./in.^{2})	4·00
(Allowing for mid-wire drop—unbalanced loads.)	
Total	8·25

	Percentage voltage drop
Referring to Fig. 5.	
33/6·6 kV transformer regulation—Tap change variation	1·25
(0·9 per cent. at unity p.f.)	
(5·0 ,, ,, ,, 0·8 p.f.)	
6·3/0·409 kV transformer regulation	3·00
(1·1 per cent. at unity p.f.)	
(3·3 ,, ,, ,, 0·8 p.f.)	
Network variation	4·00
Services	1·00
Total	9·25

It will be appreciated that the supply system materially affects the design of the primary sub-stations, and in preparing any scheme full consideration should be given to this matter.

When supplies are given at medium and low voltages the radius of supply is comparatively restricted, and a limit may soon be reached beyond which it is more economical to provide an additional sub-station to augment the area served. Rapid growth of load on existing M.V. networks necessitates frequent additions to the number of sub-stations to ensure normal loading, reasonable spacing, and good voltage regulation. At the present time a capacity of up to 3,000 kVA for 6·6 and 11 kV systems appears to be regarded as a reasonable maximum for general supply sub-stations. When planning a distribution system, a feature of importance is the facilities for extension—increasing the number of sub-stations without interrupting or materially affecting existing consumers—and isolating faulty sections of the system. Whilst the teeing-off method is simple and cheap, it does not afford the

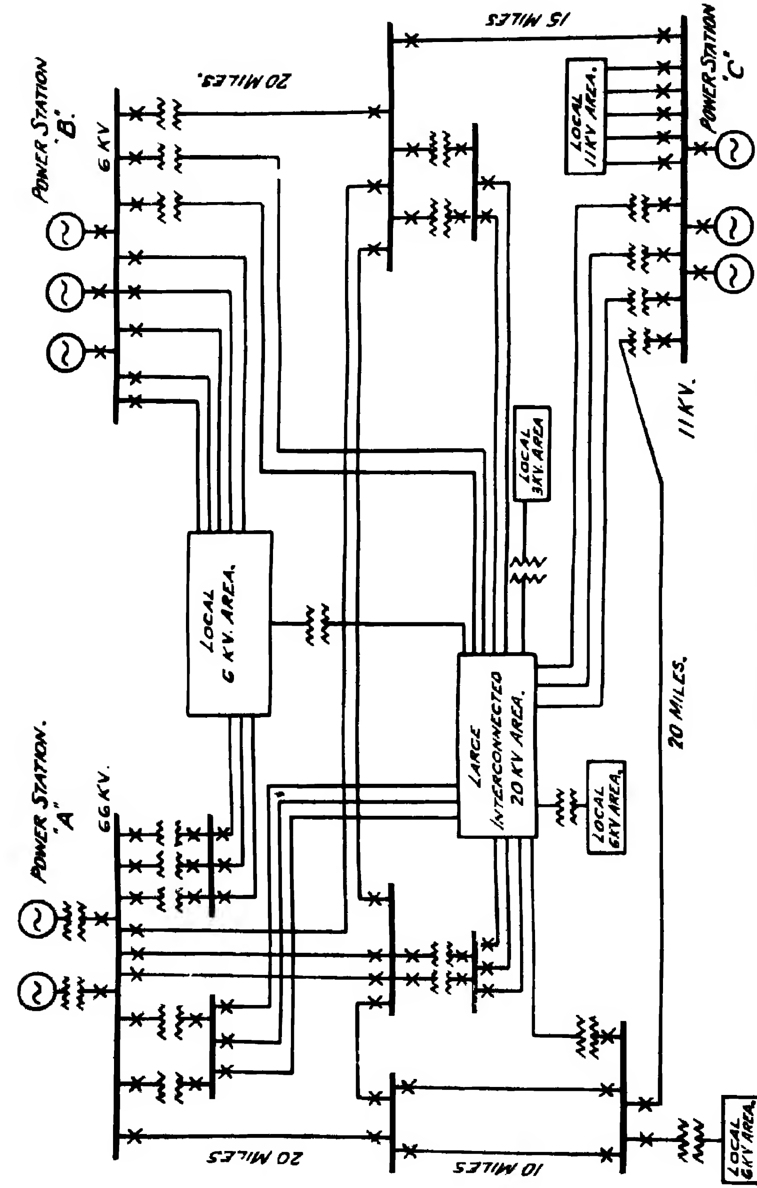


FIG. 10. Large interconnected high voltage system.

facilities necessary on an important higher voltage networks, therefore the duplicate feed, or loop-in and out methods, have to be considered. Fig. 6 shows the application of a ring main unit for such a system, and the following are the principal features :

(1) The ring, or spoke, must be capable of being broken at each transforming point.

(2) The transformer must be arranged so that it can be isolated without interfering with the ring.

(3) The transformer must be supplied from either side of the broken ring, with the ring either closed or open.

(4) Small space is required for this equipment, which makes it particularly suited to city buildings where space is generally limited.

(5) Where a large number of units are likely to be required, the cost is reasonably low.

In planning distribution networks it is desirable to estimate the probable maximum capacity of plant required, and make provision when fixing the size of sub-station. In this way, allowance can be made for the subsequent installation of larger transformer units without any serious alteration to the higher and medium voltage switchboards or building space.

Figs. 7–10 show typical systems.

Standardisation. Challenged by the need for quick construction on power supply systems some engineers have adopted the principles of mass production on their constructional programmes. The great difficulty is establishing a capacity figure for each sub-station which may ultimately be more than doubled before it is finalised. Such a procedure demands considerable flexibility which may be obtained in the following ways :

(1) Sites purchased are fairly large ; land costs are usually reasonable in the country. This provides for future expansion and prevents building up and permits of additional feeders or lines to be taken out.

(2) One end of each busbar is kept open for possible extension unblocked by permanent structures.

(3) Space is provided for duplicate busbars, double circuit breaker installation (where ultimate requirements may justify same), although initial equipment may be small.

(4) Control rooms are liberal in size having regard to cost.

(5) Provision is made for possible incidental equipment not at first required such as carrier equipment, supervisory control apparatus and telemetering equipment, etc.

(6) Sub-stations are made up, so far as possible, from standard parts.

Standardisation is most important and by making each sub-station assembly of standard units rather than adopting special details, much time is saved in design, construction and materials. Standardisation has permitted rapid completion of units even with a newly assembled construction department. Design and stocking of standard parts—steel structures, busbar materials and pedestals, transformers, portable temporary control rooms, etc.—have helped considerably. Much drawing office work is saved and the construction staffs become familiar with details and arrangements.

With standardised construction, steel and other parts for a number of sub-stations can be put on one order thereby reducing the costs ; fabricator has the design already made and shorter delivery dates are possible and design costs are eliminated ; supply authorities design work and erection labour is considerably reduced ; most steelwork and other parts can be ordered before the sub-station is designed ; same steelwork can be made suitable to cover, say, 6·6, 11 and 33 kV installations and extensions to existing sub-stations is facilitated.

Standardisation should not, however, be done for its own sake entirely, but rather for the benefits that can be gained from it and nothing should be done which will tend towards the stifling of any development. Such a risk is always present when considering standardisation.

Bibliography

T. H. Carr. "Planning Distribution Centres," *The Electrician*, 15th May, 1942.
" "Electrical Supplies to New Housing Estates," *B.E.D.A. Bulletin*, June, 1947.
" "Supply for Housing Estates," *Electrical Industries*, November, 1947.
" "Electricity Supply to Housing Estates," *Electrical Engineer and Merchandiser* (Aus.), 15th November, 1947.
E. Dannatt and J. W. Dalgleish. "Electric Power Transmission and Interconnection." (Pitman.)
J. Eccles. "The Efficient Rating and Disposition of Supply on High-Voltage Urban Systems," *Journal I.E.E.*, 1937, Vol 81.
C. A. Gillin. 'The Design of Distribution Networks," *Proceedings I.M.E.A.*, 1920.
R. W. Gregory. "Sub-station Design with particular reference to Metal-clad Switchgear," *Proceedings of Conference on High Tension Systems*, Paris, June, 1925.
R. O. Kapp. "Elect ical Transmission and Distribution." (Pitman.)
J. W. Leach. "Standardisation of Distribution in Densely Loaded Areas," *Journal I.E.E.*, Vol. 88, 1941.
T. D. Martin. "A.C./D.C. Conversion," *Electrical Review*, 2nd August, 1946.
G. O. McLean. "The Planning of an Electricity Board's Distribution System," *J.I.E.E.*, 1951.

J. W. MEARES and R. E. NEALE. "Electrical Engineering Practice." (Chapman & Hall.)
B. L. METCALF. "Transmission and Distribution of Electricity in Mines," *Journal I.E.E.*, 1944, Vol. 91 (Part 2).
V. A. PASK and R. W. STEEL. "The Development of Electricity Supply in a Rural Area," *Proceedings I.M.F.A.*, 1937.
L. ROMERO. "The Distribution of Electricity in Cities and Towns," *Proceedings I.M.E.A.*, 1928.
H. WADDICOR. "The Principles of Electric Power Transmission." (Chapman & Hall.)
H. F. G. WOODS. "Distribution of Electricity in Rural Areas," *Proceedings I.M.E.A.*, 1928.

CHAPTER II

TYPES OF SUB-STATIONS

As far as public supply undertakings are concerned, it is usual to classify sub-stations under the following sections :

(1) Primary sub-stations.

(2) Secondary sub-stations.

(3) Bulk supply and industrial sub-stations.

(4) Public or general service sub-stations.

Primary sub-stations are by far the most important distribution centres and usually consist of 66, 33 or 11 kV incoming feeders trans- 6·6 or 3·3 kV, then supplying secondary sub-stations and possibly some industrial sub-stations. The layouts will depend on many conditions, and what is found suitable in one locality will probably be unsuitable in another. Primary sub-stations include the national grid transforming stations, which are operating at 132, 66 and 33 kV.

Secondary sub-stations are in some cases equal in importance to the primary sub-stations, but much will depend upon the areas served. The switching and transforming plants have to be accommodated, whilst it may be necessary to provide supply for traction purposes (trains, trams and trolley-buses) from the secondary sub-station, and converting plant would be required. High voltage interconnections are usual with secondary sub-stations.

Bulk supply sub-stations usually have two transformers, one acting as stand-by. By interconnection on the medium voltage sides of transformers, other sections of the network may be supplied in an emergency. In very large industrial works, embodying shipbuilding, workshops, foundries, etc., it may be necessary to have a high-voltage ring covering the entire area, with several sub-stations at suitable distributing points.

General service sub-stations vary considerably, and include brick built stations to kiosk type transformer equipments and pole mounting fixings. Underground transformer pits, with nearby fuse-kiosks, or disconnecting boxes, are also in use

The types of sub-stations may be summarised as follows :

(a) Outdoor.
(b) Indoor.
(c) Basement or Underground.
(d) Cinematograph.
(e) Kiosk.
(f) Pole mounted, or Overhead.
(g) Mining.
(h) Mobile.

Further sub-divisions may be made to differentiate between rotary and static sub-stations and automatic and manual sub-stations, Fig. 11.

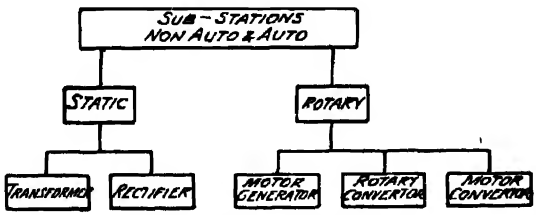


FIG. 11. Classes of sub-stations.

In some cases both A.C. and D.C. will be necessary, thus entailing the inclusion of two types of plant in the same station. A typical example is where a sub-station is required to provide both a general distribution network and a traction system.

Rotary sub-stations include motor generators, rotary convertors and motor convertors, although the present tendency is to use rectifiers where D.C. is required. Motor generators and motor convertors, unlike rotary convertors, do not require a step-down transformer, and so permit a simpler layout of plant and building.

Outdoor Sub-stations. Speaking generally, these only comprise static equipments, Figs. 12 and 13. One problem which confronts the sub-station designer repeatedly is whether the plant should be housed or placed out-of-doors. With indoor working the costs of transformers and switchgear are rather less, whilst inspection and maintenance can be carried out under more favourable conditions, and there is protection from the weather, etc. On the other hand, with outdoor working, no buildings, apart from fire sectioning walls, or ventilation equipment, are required. Although the need for buildings may not exist in the early stages of development, the layout of the plant and the construction of foundations and cable trenches can be arranged so that a building can be erected later. The major items of

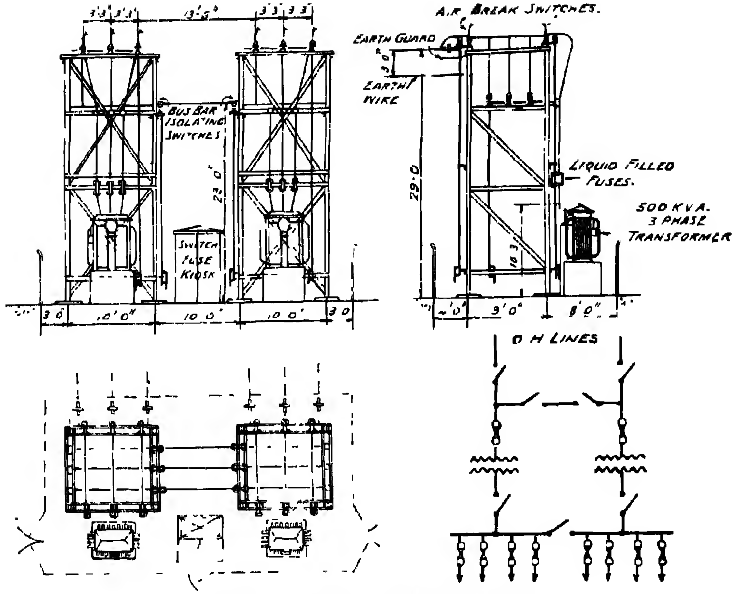


FIG. 12. Outdoor type sub-station.

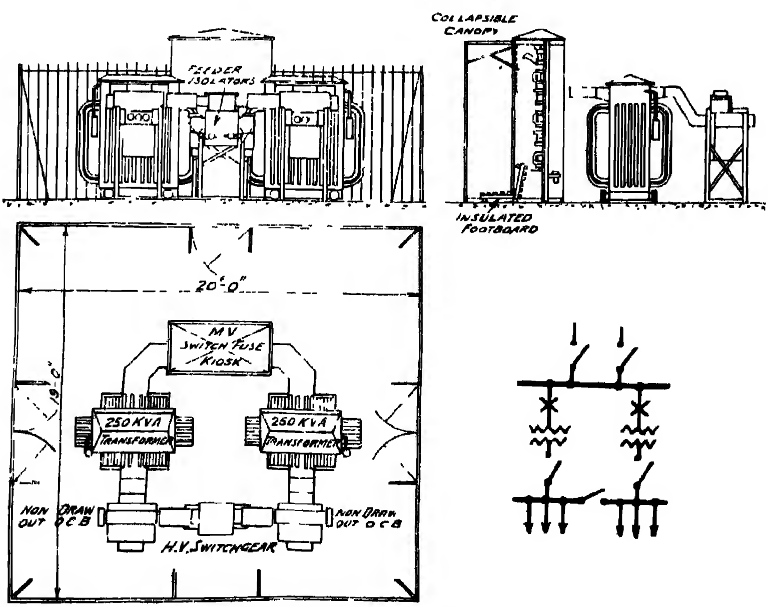


FIG. 13. Outdoor type sub-station.

plant, such as transformers and circuit breakers, are usually mounted on concrete plinths at ground level. The raft type is useful in rural and urban areas as it can be tucked away near the load centre. It is

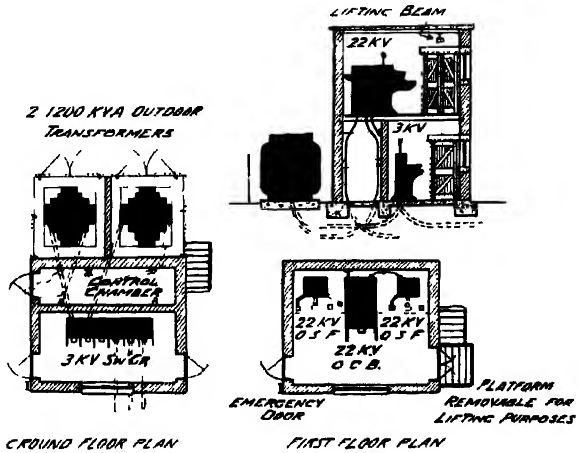


FIG. 14. Duplicate industrial sub-station with outdoor transformers, "single-switch" type.

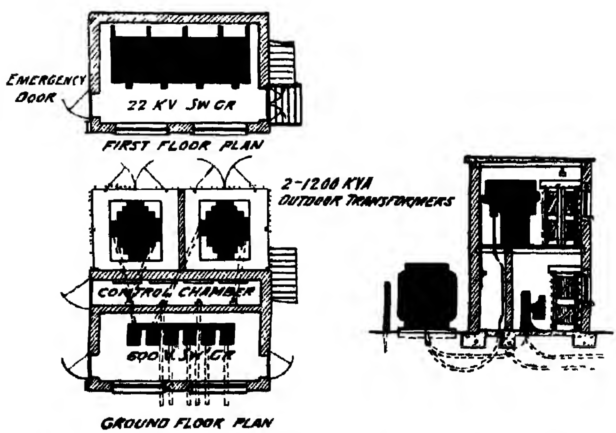


FIG. 15. Duplicate industrial sub-station with outdoor transformers (22 kV/600 V).

usual to include a fence surround if switch and fusegear are installed. The whole of the equipment must be of robust design and construction to withstand the climatic conditions obtaining, and particular

attention should be paid to the rapid removal of rainwater where ingress to vital parts would prove disastrous. On outdoor equipment, springs should be kept to a minimum. Where these cannot be semi-enclosed and packed with grease, phosphor-bronze should be used, with a large factor of safety. Small stranded conductors should also be avoided.

Such sub-stations ~~are in service~~ with voltages up to 220 kV and have given but little trouble. Failure of high voltage outdoor equipment may result in heavy arcing ~~and consequent danger to~~ both personnel and plant. It is found that metal screenwork forms an effective barrier in limiting the arc spread.

The grid sub-stations operate at 132 kV, and to meet the varying site conditions a number of different types are employed. With these higher voltages, outdoor sub-stations are cheaper, and the danger of explosion ~~and fire is reduced~~. Further, the inspection of the equipment is comparatively simple. The control and protective equipments, etc., are housed in a nearby building.

~~For industrial and city areas, a compromise~~ is often effected whereby the transformers are placed out-of-doors and the switchgear is housed, Figs. 14 and 15.

As the grid sub-stations are of special interest some details are given.

The 132 kV sub-stations are of the outdoor type. There are two

TABLE 4. *Grid Sub-stations*

Type	Description	Application
L.N.E.	Low non-extensible (3 circuit breakers)	For grid supplies where only future extensions of transformer capacity are contemplated.
H.N.E.	High non-extensible (3 circuit breakers)	
L.E.	Low extensible (3 circuit breakers)	For grid supplies where extensions of switchgear beyond the capacity of the single-circuit breaker layout will be necessary.
H.E.	High extensible (3 circuit breakers)	
L.D.B.	Low double busbar	For grid supplies at the most important generating stations.
H.D.B.	High double busbar	
C.	Connections only (between lines and transformers).	For transformer feeders only.

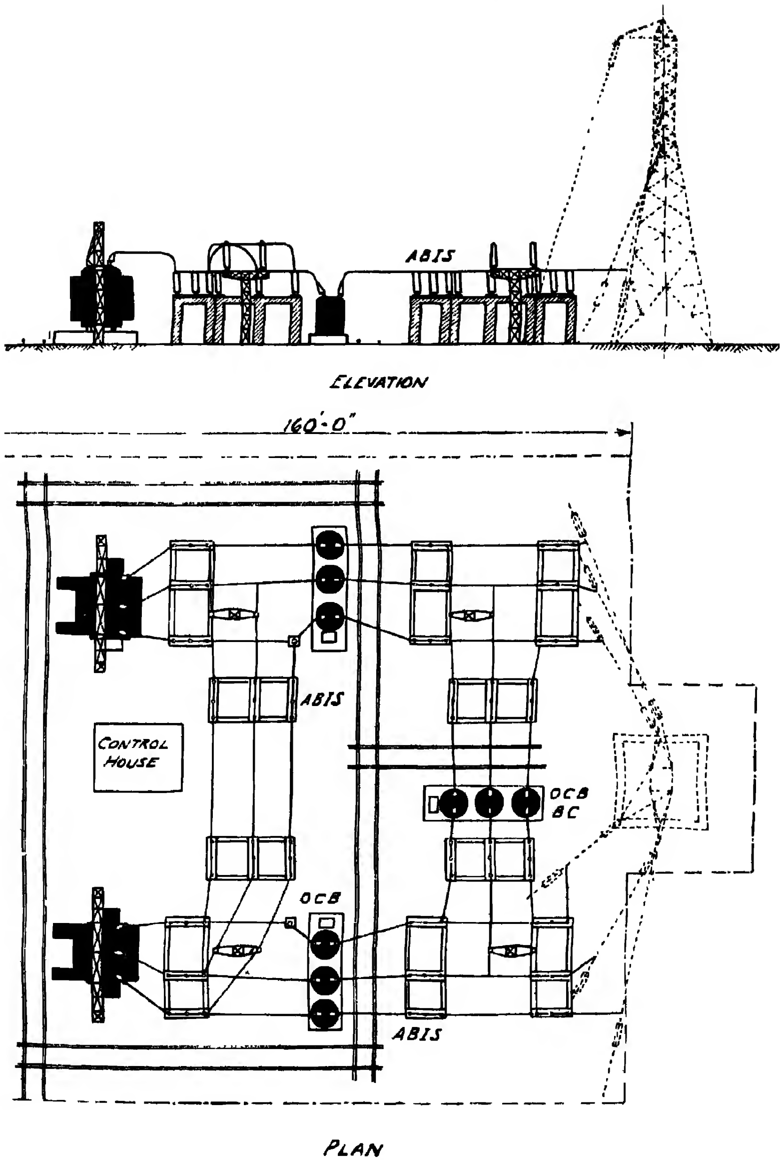


Fig. 16. Type L.N.E. 132k V sub-station.

classes—high and low, Table 4, the former being used where ground area is limited, and the latter where adequate area is available.

The " Low " types (Figs. 16–22) are built on land large enough to accommodate the switchgear and transformers, the isolating switches being placed as near to ground level as safety considerations permit. The structural steelwork and cost of maintenance are reduced and

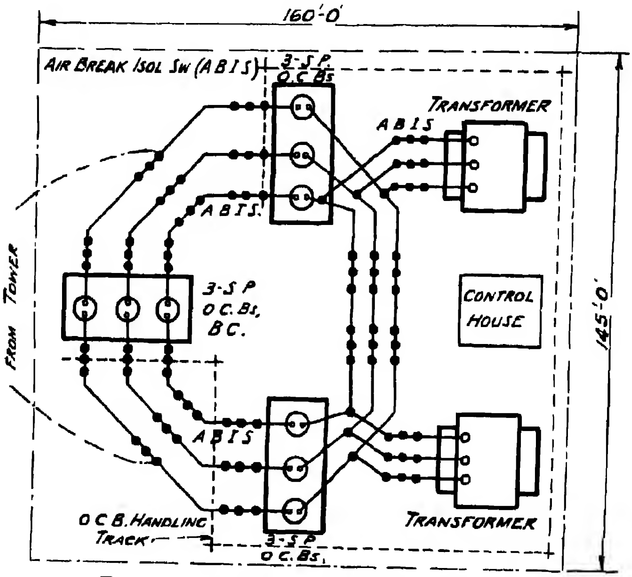


FIG. 17. Low non-extensible (L.N.E.) sub-station.

operation and inspection facilities are improved. Reinforced concrete structures are used, thereby avoiding painting.

The " High " types (Figs. 23–27) require more structural steelwork, and the higher levels make maintenance and inspection more difficult and costly. Fig 28 shows the transformer-feeder station layout.

The equipment for two 132 kV lines and two transformers consists of :

By-pass connection to allow each transformer to take power from either of the overhead lines.

Isolating switches between the lines and the circuit breakers and the transformers.

Three circuit breakers, one between each 132 kV line or feeder and each transformer, and one in the by-pass.

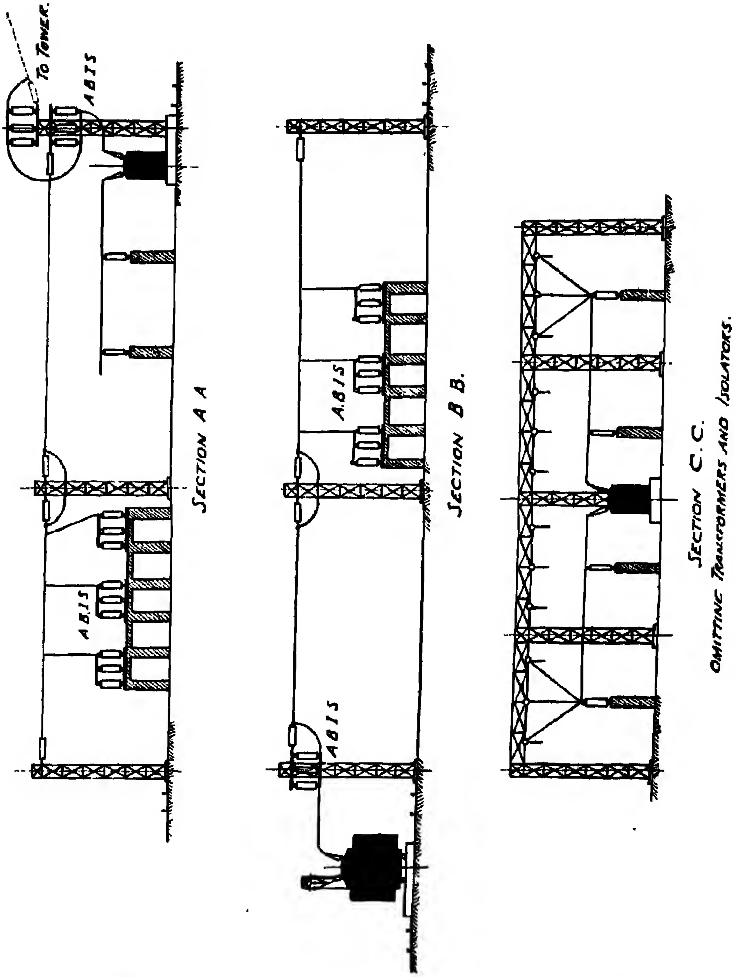


FIG 11 L.E. 132 kV sub-station.

Instrument current transformers ; feeder protective current transformers, and transformer protective current transformers.

The by-pass connection is normally open.

Should a fault occur in a line section, one transformer circuit

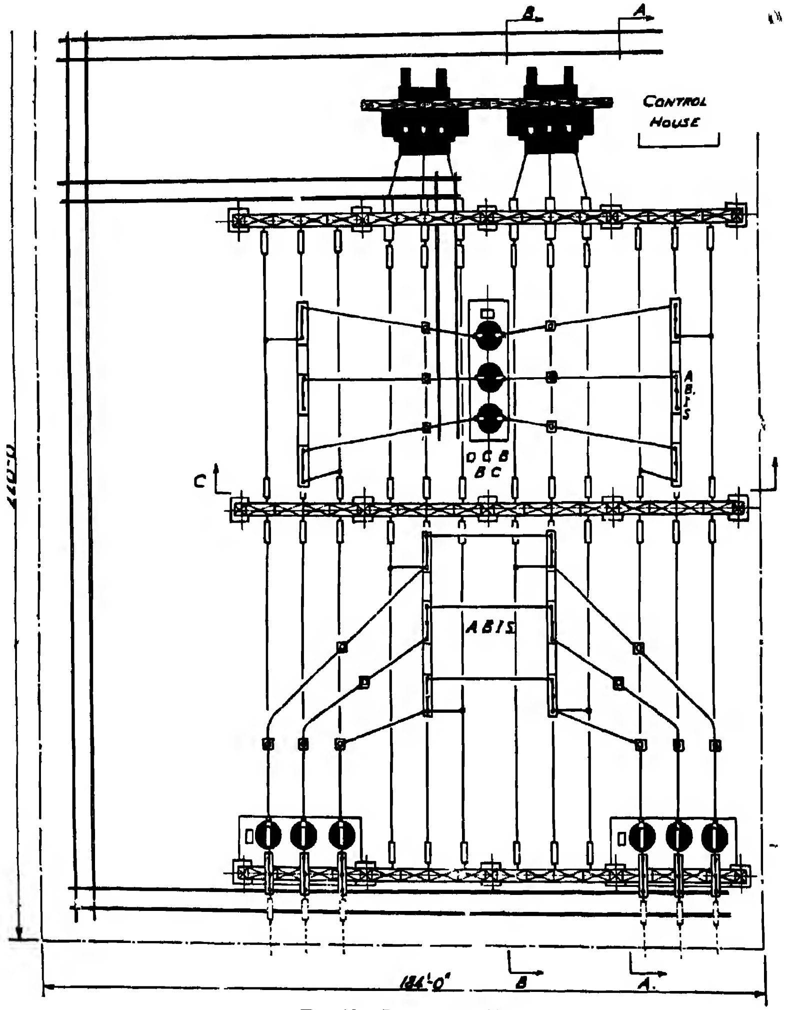


Fig. 19. Plan of Fig. 18.

breaker and the bus section breaker open automatically. This complicates the protection to some extent, but this disadvantage is outweighed by the saving in cost due to the omission of two circuit breakers. The by-pass isolating switches enable each transformer to be connected to either line when any circuit breaker is out of commission.

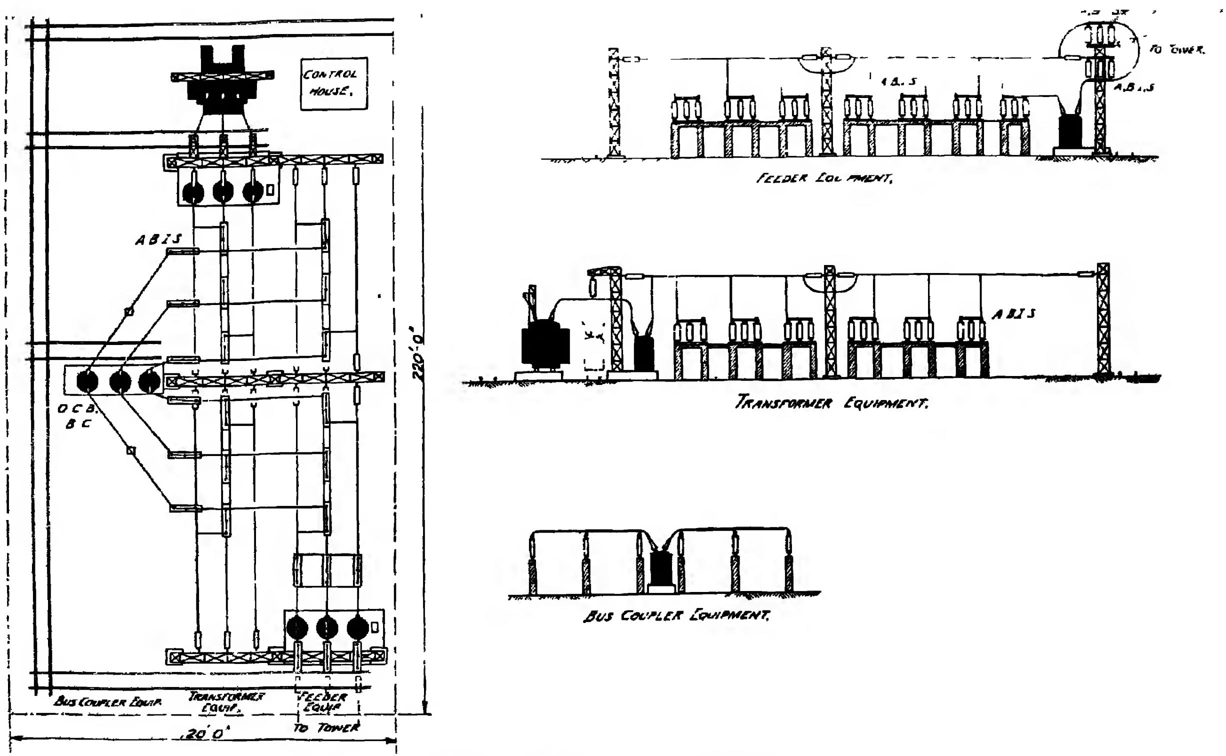


Fig. 20. Type L.D.B. 132 kV sub-station.

Two isolating switches are used in series to permit of cleaning and general maintenance being carried out without having to shut down the sub-station completely.

The 132 kV circuit breakers consist of three single-phase units, each contained in an oil-filled tank interconnected mechanically and operated simultaneously by solenoid mechanism taking a supply from

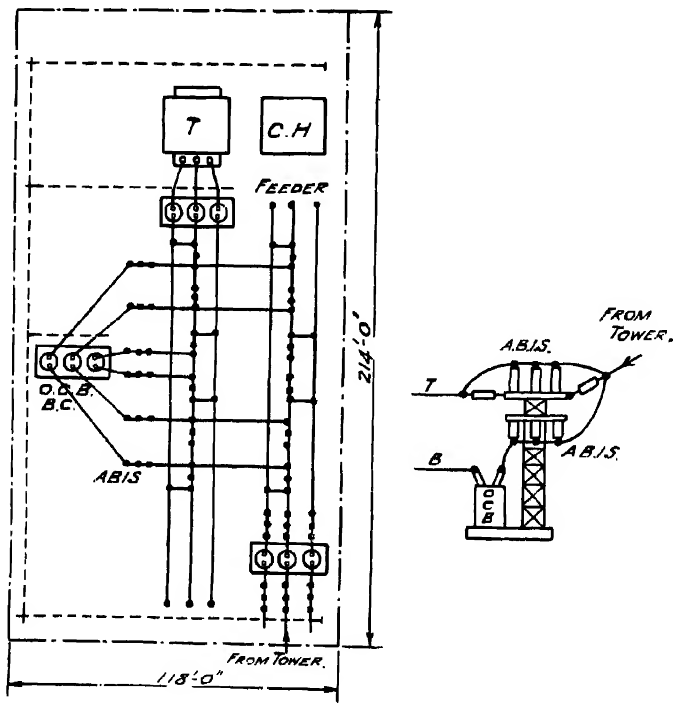


FIG. 21. Low duplicate busbar (L.D.B.) sub-station.

a 110-volt battery. Manual operation is provided as a stand-by. Oil-filled bushings fitted with arcing horns form the terminals of the circuit breaker units. A manhole is included in the cover to permit of entry for inspection and maintenance of the electrical contacts. The rupturing capacity of the complete three-phase unit is 1,500 M.V.A. The isolating switches are of the rotating centre-pillar type and the three switches are operated simultaneously. The isolators are inter-

locked with the circuit breakers to prevent breaking load on the isolators and are hand operated from ground level.

The minimum spacing between phases is 9 ft., and from live metal (except arcing horns and rings) to earthed metal the minimum is $4\frac{1}{2}$ ft. The clearance from live metal to earth is not less than from arcing horns and rings to earthed metal.

The lattice girders are of galvanised steel, and there is a factor of safety of $2\frac{1}{2}$ for the completed structures, based on specified maximum working loadings. The outdoor busbars are of hollow copper tube 0·9 in. diameter, with a sectional area of 0·3 in.^{2}. Suspension type insulators are used but for compression and tension supports post type insulators built up of standard units are adopted.

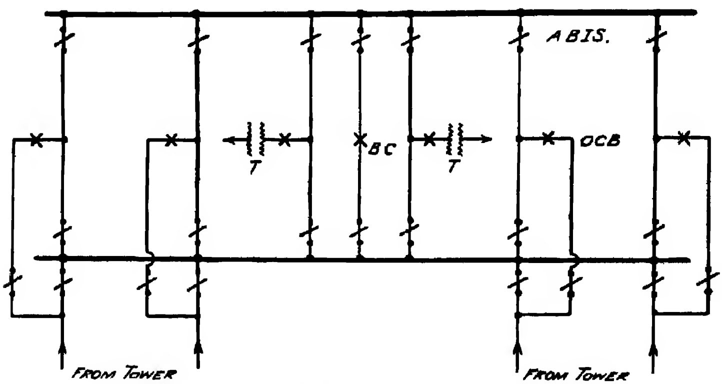


FIG. 22. Main electrical connections (L.D.B.).

The transformer units in the 132 kV sub-stations vary in outputs from 7,500 kVA to 75,000 kVA. For transformers up to 10,000 kVA, natural oil cooling (O N) is used. Above this capacity, oil cooling is used for half load or slightly more, and for higher capacities forced oil cooling, with air blast cooling, is added. Air blast cooling may be used on an external cooler (O F B), or, alternatively, air blast, with air jets impinging directly on the radiators of the tank (O B), is added.

The 132 kV windings of the transformers are star connected, the neutral point being earthed direct. The lower voltage side is delta connected. On load tap-changing equipment is fitted on the 132 kV side for voltage regulation with a variation of + or — 10 per cent.; there are usually fourteen steps of 1·43 per cent. The tap changers

can be hand operated or motor driven with remote electrical or fully automatic control. Conservator tanks are fitted, and Büchholz relays are included. Gas bubbles evolved by faults developing in the wind-

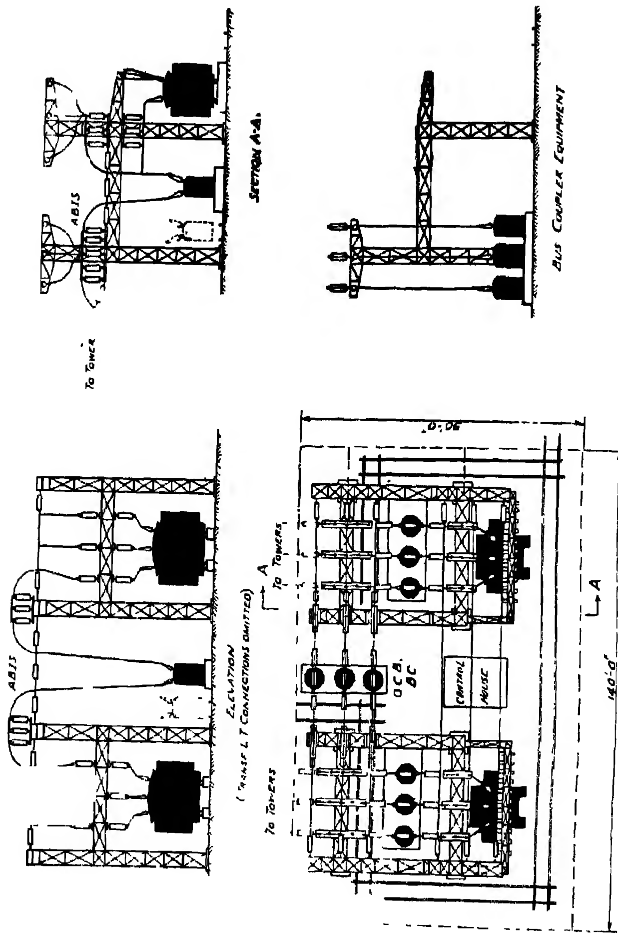


Fig. 23. Type H.E. 132 kV sub-station.

ings or other parts of the transformer magnetic or electric circuits, on entering the alarm device, operate audible warning circuit, or, in the event of a breakdown, operate the tripping circuit of corresponding circuit breakers. The lower voltage side of the transformer has a

separate auxiliary and earthing transformer connected direct to the phase leads. It is an interconnected star winding connected to the phase leads and a star connected tertiary winding for auxiliary services in the sub-station.

Earthing of all apparatus is by means of copper connections, the main connection (0·25 in.²) being taken round the station. An earth plate is buried at each corner of the system, each cast iron plate having an area of 16 ft.², or, alternatively, a number of 6-in. cast iron pipes of equivalent area. To ensure close contact with the earth, the plates and pipes are laid up in a 6-in. layer of finely divided coke.

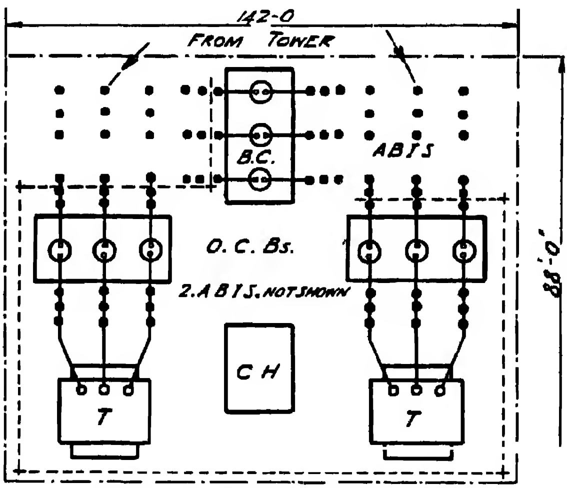


FIG. 24. High extensible (H.E.) sub-station.

The lower voltage, 66 kV and 33 kV, switching and transforming stations are generally of the following types :

(1) Large important switching stations with double busbar circuits and sectionalising circuit breakers, where the switchgear may either be of the outdoor or indoor types. The breakers are remote electrically controlled, taking their supply from a 110-volt battery. The battery capacity is 250 ampere-hours for ten hours, and serves for closing and tripping, emergency lighting and indicating lamps.

(2) Lesser important sub-stations, with ring arrangement of circuit breakers and the circuits tapped from the connection between the breakers ; sectionalised single busbars are used.

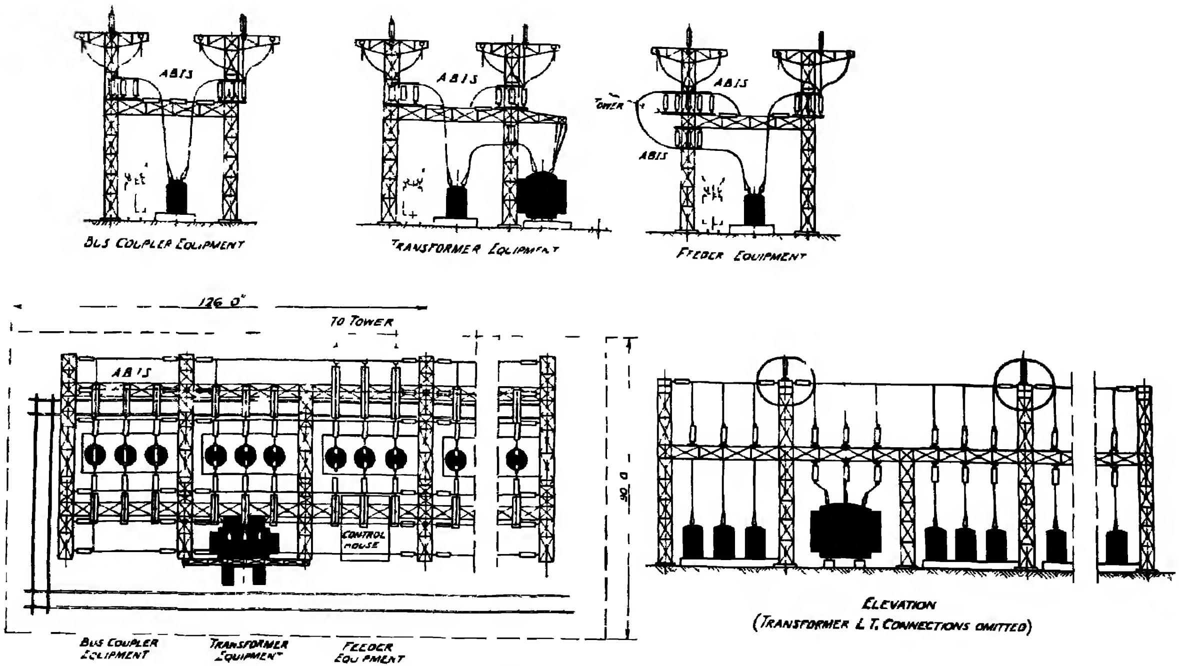


FIG 25 Type H.D B 132 kV sub-station

(3) Three-circuit breaker and one-circuit breaker arrangement of sub-stations. The former has a section switch in the line and a branch switch for each transformer. The latter has no switch for the transformer, only a circuit breaker.

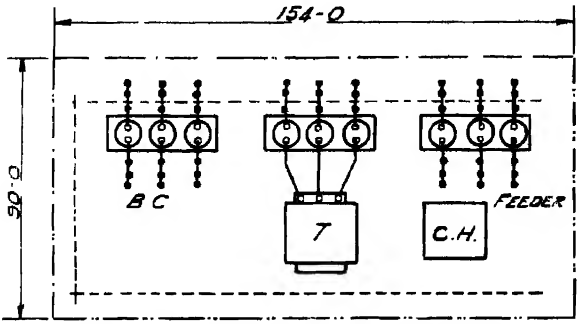


FIG. 26. High duplicate busbar (H.D.B.) sub-station.

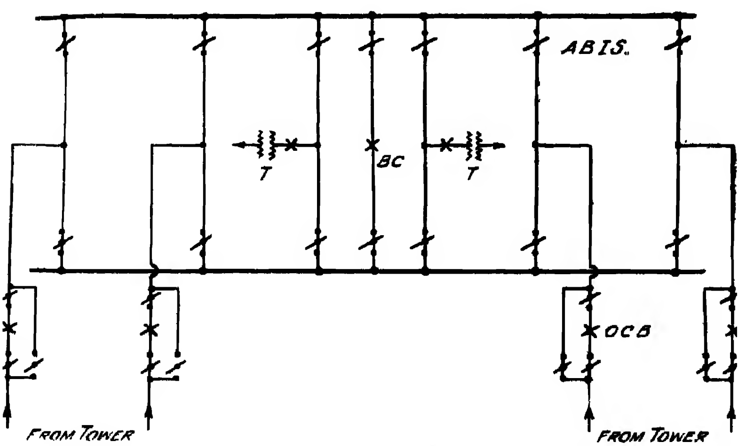


FIG. 27. Main electrical connections (H.D.B.).

(4) Transformers feed directly to the supply lines through isolating and earthing switches, and in some cases protective fuses.

(5) Small unattended stations with hand-operated circuit breakers. Tripping is by means of 30-volt alkaline batteries.

Transformers are of the three-phase, natural-oil-cooled type for

capacities up to 10,000 kVA, and air blast for higher capacities. Off-load tapping switches are fitted to transformers up to 2,000 kVA, and on-load tap-changing equipments for larger capacity transformers. The primary windings of 66 kV transformers are star-connected, and the secondary windings delta-connected. Star-star connected transformers have a delta-connected tertiary winding of 25 per cent. of normal rating.

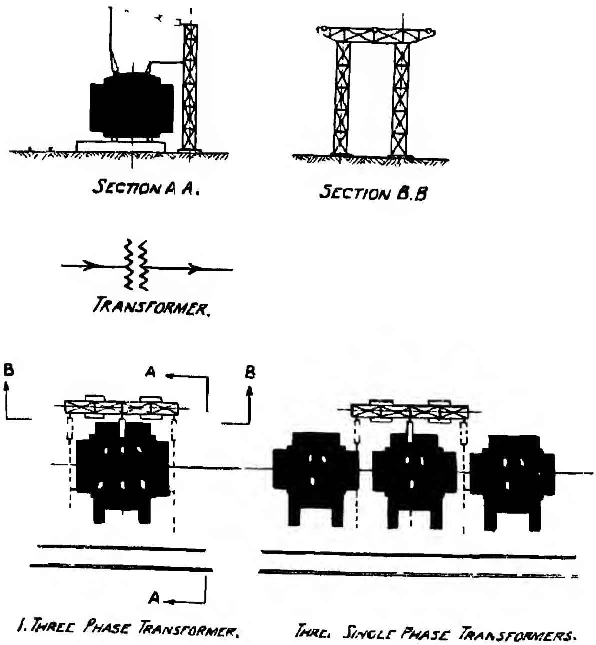


Fig. 28. Type " C " 132 kV sub-station.

Auxiliary and earthing transformers are provided for sub-station services. Cast iron earth plates 4 ft. square by ½ in. thick, or, alternatively, 6 in. diameter by ½ in. thick cast iron pipes are buried in finely divided coke and connected together by means of 0·1 in.² copper connections.

Standard equipments for transformer feeder circuits consist of :

One isolating switch, one circuit breaker, three indicating instru-

ment current transformers, and three protective gear current transformers.

A panel on which is mounted one circuit breaker control switch,

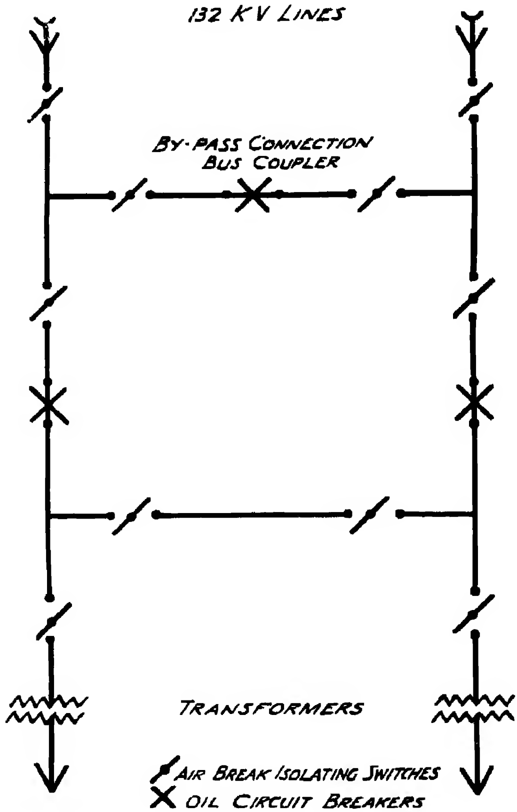


FIG. 29. Main electrical connections (L.N.E. ; L.E. ; and H.E.).

one three-way ammeter switch, protective relays, synchronising sockets, and alarm bell switch.

An indicating panel with diagram of connections showing open and closed positions of circuit breaker and isolating switches, together with indicating lamps showing automatic tripping of the circuit breaker. Figs. 29–31 show main electrical connections.

Indoor Sub-stations. These stations include both static and rotary plants, and may also provide for both manual and automatic operation. The whole of the plant and equipment is under cover, which results in a higher overall sub-station capital cost.

In city and certain residential areas the indoor station (Figs. 32–34) is frequently adopted, even for transformer equipments. It is advisable to standardise the layouts so that the buildings are generally of the same construction in so far as materials and constructional details

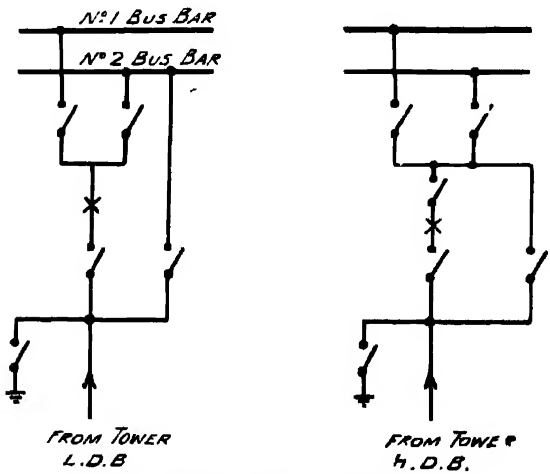


Fig. 30. By-pass isolating switch connections.

are concerned. Difficulty is often experienced in obtaining adequate or regularly shaped sites, and modifications are inevitable. Electrical equipment in permanent sub-stations can usually be extended without much inconvenience, and any surplus distributor copper can be used. Kiosk installations are never quite so good in so far as additions thereto are concerned.

In affording a supply to a housing estate, it is desirable that an alternative supply should be provided wherever practicable and economic for many hundreds of families can be inconvenienced should a failure occur. The siting of housing estates does not come within the province of the supply authority and it is usual to receive a plan showing the proposed layout of the estate which enables preliminary work to be commenced. The sub-station will generally be sited by the planning authorities and it serves as a starting point in the planning

of the network for affording supplies to the various groups of houses. Sites are usually restricted and may prove uneconomic in respect of cabling, unless a number of smaller high voltage supply points (trans-

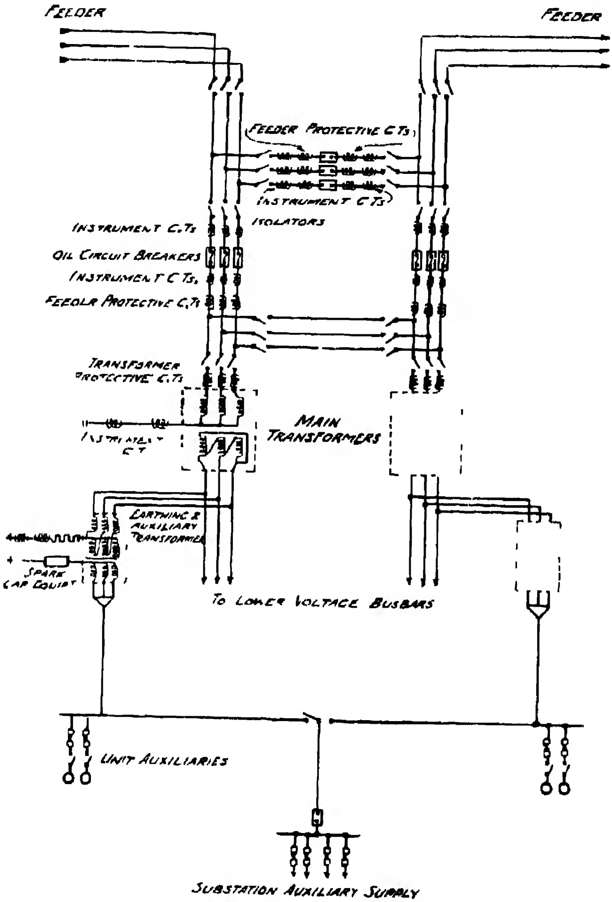


FIG. 31. Diagram of connections for 132 kV 3-circuit breaker transforming station.

former units) can be utilised. Medium voltage copper costs can become excessive and care is required to ascertain the possibility of using more smaller transformer points. An estimate will have to be prepared of the anticipated loading and reference can often be made to

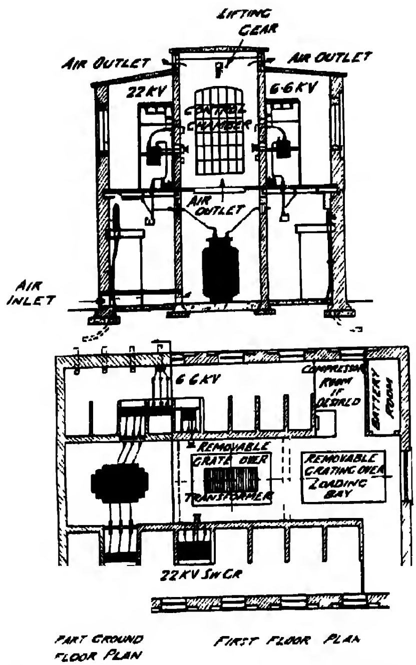


FIG. 32. Sub-station with cellular type switch-gear (suitable for O C.B.s or A.B C.B.s)

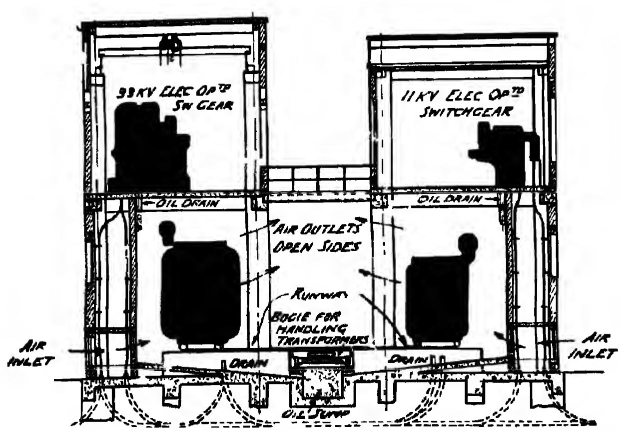


FIG. 33. Typical large sub-station for bulk supply to city (33/11/22 kV).

existing statistical data. Comparing two housing estates the average annual consumption is as follows :

	Estate 1	Estate 2
Consumers with cooker	1,600	2,100
Consumers without cooker	400	500

The estimated annual consumption given by one authority, based on a family of four persons for fifty weeks per year is :

	kW h
Cooking	1,300
Wash boiler	300
Refrigerator	300
Immersion heater	650
Lighting, radio and occasional radiator	650
Total	3,200

A demand of 1 kW per domestic consumer may be assumed as an average figure for normal conditions. Load factors of 20–25 per cent. have been recorded, based on maximum demand for Christmas Day, with general figures of from 10–15 per cent.

A typical indoor sub-station will be described and is representative of a housing estate for a large industrial city. The buildings accommodate two transformers, with a H.V. supply of 6·6 kV and medium voltage 415 V. Wall surrounds or fences are omitted in spite of difficulties sometimes experienced with children on housing estates. Windows are not included and the choice of materials was largely dictated by the desire to provide a pleasing appearance. Sandstone was at hand and it was used for building facing of the exterior walls. The main walls are 12 in. thick, the exterior walls having hammer dressed stone with the exception of the architraves, coping, steps and lintels, which are of artificial stone. The roofs are of reinforced concrete covered with asphalt, the average thickness being 6 in., the floors are also of concrete. The interior faces of the main walls and the inner wall of the building are of selected common brick. This construction is slightly more costly than brick for exterior walls, but the site justified the additional cost which was about £100. The initial installation consists of two 750 kVA transformers, but the chambers,

switchgear and cabling are all capable of ultimately taking 1,500 kVA units. Growth of electrical load either by increased use of domestic appliances and the possibility of further estate developments (which were planned) in the immediate vicinity are, therefore, allowed for. Use is made of the existing H.V. feeder to provide a ring main supply to the sub-station. The H.V. switchgear is of the single busbar 6·6 kV, 150 MVA oil-immersed type, and the M.V. fusegear of the 25 MVA H.R.C. type. One transformer is normally in circuit, but the medium voltage fusegear can be sectionalised so that each transformer serves one-half of the outgoing distributors. The auxiliary equipment includes a 30 V. switchgear tripping battery and a private system telephone. All cable sheaths are connected to the station earth bar which is taken to an earth pipe which is buried vertically in coke breeze. The heating and lighting supplies are taken from the fusegear busbars via a 60 A. H.R.C. fuse and neutral link. The H.V. and M.V. connections between the transformers and the corresponding switchgear and fusegear are of 3-core and single-core p.i.l.c. cables respectively. A two-pair telephone cable is laid with the H.V. feeder. The incoming H.V. feeders are 3-core 0·1 in.^{2} p.i.l.c.s.w.a. and taped.

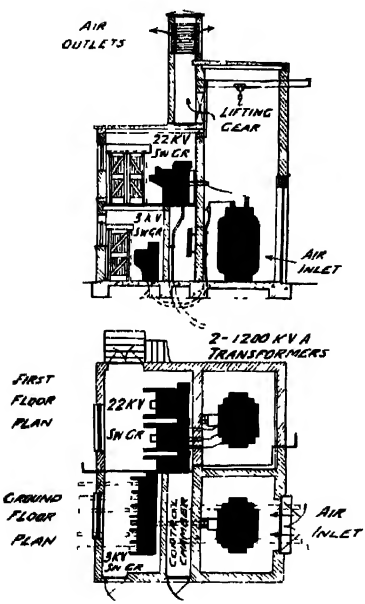


FIG. 34. Duplicate industrial sub-station with indoor transformers.

The outgoing distributors, which afford supplies to 6-way and 4-way, 300 A. fuse pillars are disposed throughout the estate, one 4-core 0·25 in.^{2} p.i.l.c. with serving but unarmoured. The outgoing cables from the fuse pillars vary from 4-core 0·25 to 0·10 in.^{2} p.i.l.c. with serving, but in certain cases smaller cables are used. The cables are laid direct in the ground and are protected by interlocking tiles, except at road-crossings where they are pulled into self-locking earthenware pipes. With the ever-changing charges for labour and materials it is difficult to give firm costs for these schemes, but the following, based on 1946 costs, is typical :

Estate 650 semi-detached houses :

		£
Sub-station building	. .	1,800
Mains, pillars and laying .	.	14,100
Sub-station plant	. . .	3,100
Total	.	£19,000

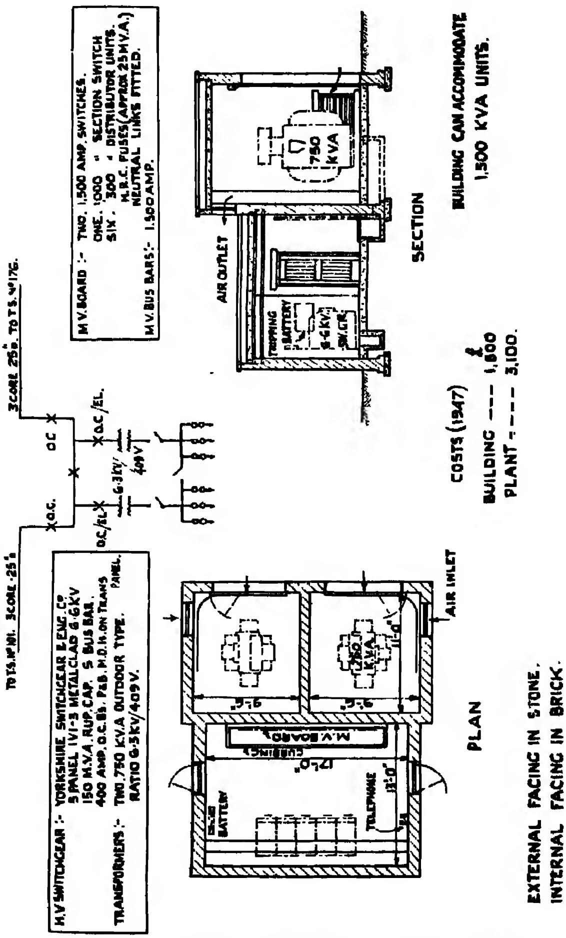


FIG. 35. Transforming Station (Housing Estate).

PANEL No						
LABEL READING			VALLEY POWER STN. (GREENGATES No 1 FEEDER)	TRANSFORMER No 2.	BUS SECTION	TRANSFORMER No 1.	[illegible]GATE [illegible] (GREENGATES No 1 FEEDER)
TYPE OF UNIT			METAL CLAD IVI-3.				
MAKER			YORKSHIRE SWITCHGEAR & ENGINEERING Co				
RUPTURING CAPACITY.			150 M.V.A.				
BUS BAR CAPACITY			400 AMP. COMPOUND-FILLED				
CURRENT TRANSFs	PROTECTION		O.C	O.C E.L.	NON - AUTO	O.C. E.L.	O.C.
	C.T. RATIO.		300/5	150/75/5		150/75/5	300/5
TRIP COILS					30V. D.C.		
AMMETER OR M.D. SCALE			0-400	P.B.I. 0-200 0-100		P.B.I. 0-200 0-100	0-400
CABLE SECTION SQ. IN.			3C. 0·25	3C. 0·25		3C. 0·25	3C. 0·25
CABLE DIA. OVER LEAD IN			1·96	1·96		1·96	1·96
CABLE DIA. OVER ARMOUR							

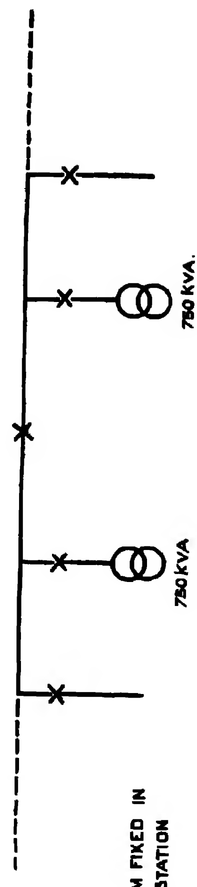


DIAGRAM FIXED IN
SUB-STATION

SUB-STATION No
DRAWING No

FIG. 36. High Voltage Diagram for Fig. 35.

Figs. 35, 36, 37 and 37A show the principal details of the sub-station described.

Basement or Underground Sub-stations. The demand for this type of station has been accentuated by the growth of demand for electricity

n city areas where sites for buildings are very limited and even then are usually of such a price as to be prohibitive. In general, it is essential o keep the sizes of such stations to a minimum and at the same time

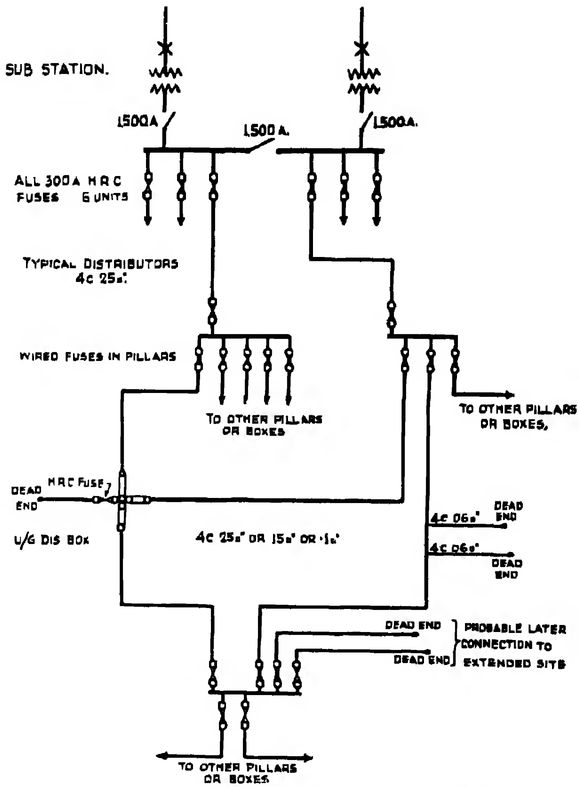


FIG. 37. Typical Housing Site Sub-station Connections.

Fuses in the sub-station and in pillars or boxes are fitted to suit the cable rating ; H.R.C. fuses in sub-station and boxes, wired fuses in pillars. Based on the above general considerations, some discrimination in fusing is possible to avoid shut down of extensive area.

Links are generally used in disconnecting boxes except where cables run to " dead ends ".

Services –2C0·0225 square inch and 2C0·04 square inch. cables are used for services depending on the length and whenever more than one house is to be supplied. Services are taken from any distributor.

provide reasonable access for both plant and personnel. It is vital that the existing fire risks of the neighbouring or accommodating

building should not be increased by the addition of such a sub-station. The plant should be contained in fire-resisting chambers or compartments to prevent the spread of fire. In some installations it may be advisable to employ air-cooled or non-inflammable filled transformers and switch-fuses to avoid bringing oil into the premises. The ventilation will also demand attention and should be independent of any trunking which is connected with other parts of the building. The structure, party walls, partitions and doors should be of substantial construction capable of resisting the effects of fire for a considerable period. Remote indication of excessive rise in temperature should

FIG. 37A.—Sub-station Building (Fig. 35).

be provided so that the H.V. supply can be disconnected. An automatic fire extinguishing equipment should also be included, together with emergency lighting of limited capacity in the main building.

Another type of basement sub-station is that which is isolated from any buildings and is placed underground. Drainage, ventilation and access are worthy of careful consideration. Supply authorities operating in cities and large towns are often forced to construct underground or basement sub-stations for primary switchgear and transformers. Underground construction is not only initially expensive, but also restrictive on extensions, which, in practice, only too often inevitably leads to a congestion of plant and unsafe conditions of operation. The advantages of placing a rectifier sub-station supplying

a low voltage D.C. network at the centre of the load are obvious, but such an arrangement is often impracticable due to the difficulty, or heavy expense of obtaining a suitable site at the desired point. This difficulty may be overcome as shown in Fig. 38, in which a 500 kW rectifier equipment is housed. The chamber has a rectangular opening in the roof through which the equipment is installed, and afterwards is covered by a reinforced concrete slab and the roadway relaid over it. Access to the chamber is by two ventilator shafts brought up alongside the footpath where they are surmounted by small louvred pillars fitted with doors through which entrance is gained. It is possible to place a sub-station of reasonable output in such a position in relation to the network it supplies that the need for a heavy untapped D.C. feeder, entailing considerable expense in copper and losses, is eliminated. The network is supplied by distributors radiating direct from the suitably-placed sub-station. Figs. 39 and 40 show alternative types.

Cinematograph Sub-stations. These are generally of the indoor type, and the desirable features to be embodied in their design have been referred to. Motor generators and/or rectifiers are housed in a separate room.

Kiosk Sub-stations. This type (Figs. 41–43) is much cheaper than a permanent building, and it has a further advantage of being semi-portable, which is a valuable feature where networks are likely to expand very rapidly due to growth of load.

It can be recovered and used elsewhere should it be necessary to replace it by a larger sub-station and can be transported as a unit to the site.

In an attempt to reduce the capital cost of providing a supply in areas where the immediate revenue return is not likely to meet the annual charges, a steel-plate construction has been adopted to accommodate the switching and transforming plant. Various forms of sheet-steel kiosks are available for bolting direct to prepared concrete plinths or foundations. The steel plate kiosk is considerably lighter, more robust and generally cheaper than one of cast iron. Further, it has greater flexibility in design and dimensions can be varied without much cost. Apart from the saving in building costs, there is a saving in site area and consequent rent, but maintenance charges (painting, etc.) will generally be greater.

The kiosks are made up in sections and can be arranged to provide for extension should the need arise due to increased local development.

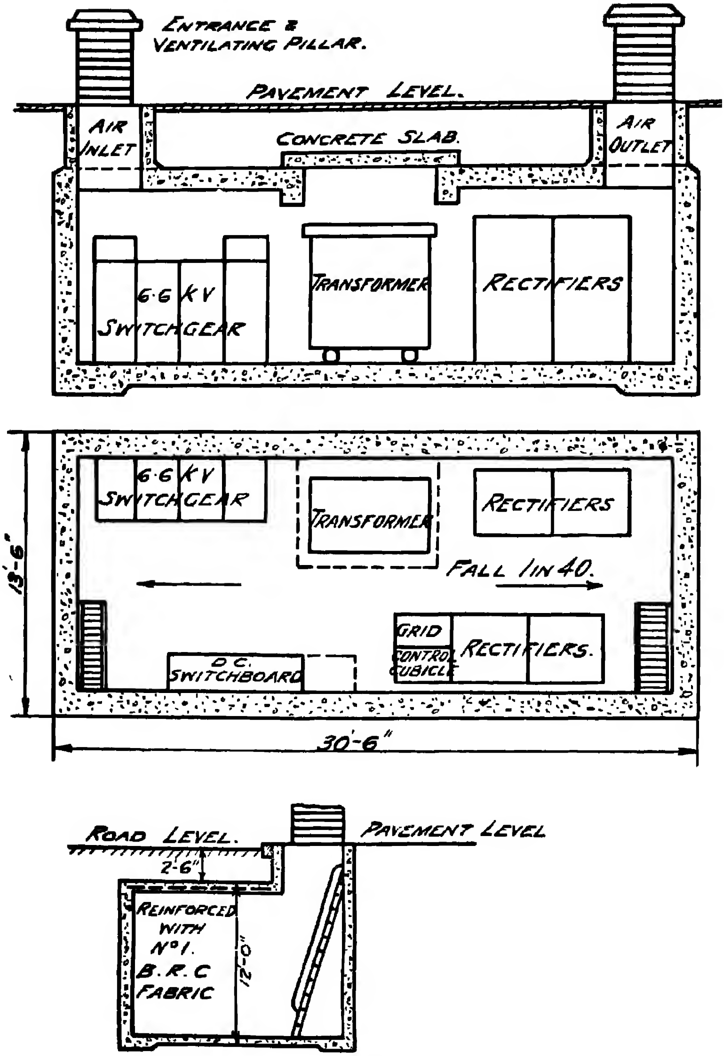


FIG. 38. 500 kW rectifier underground sub-station.

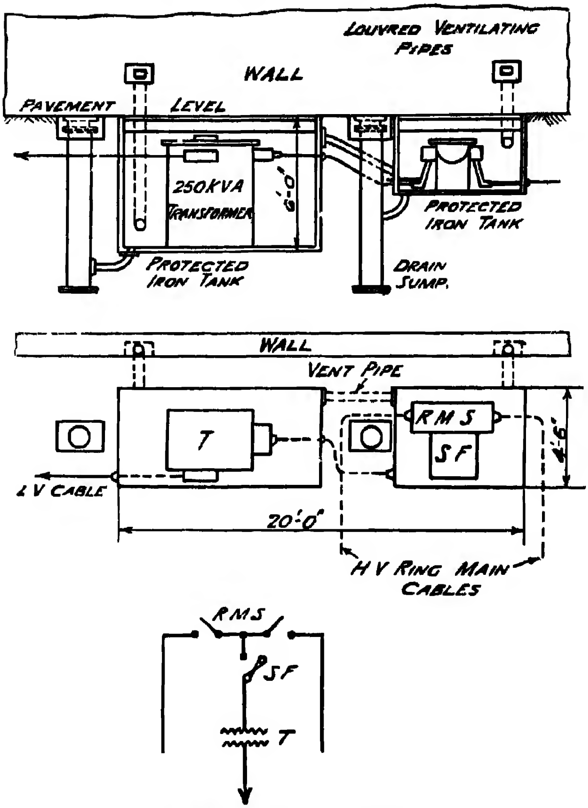


Fig. 39. Underground type sub-station.

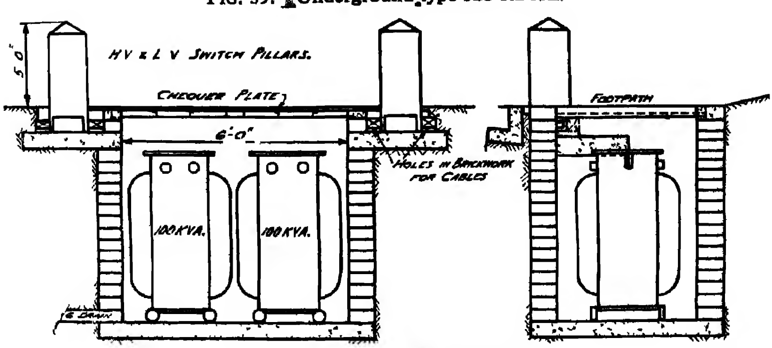


Fig. 40. Pavement transformer pit.

There is practically no limit of size to which kiosks can be made by assembling them in sections ready for bolting together on site. Sheet steel of not less than $\frac{1}{8}$-in. is satisfactory. The arrangement of equipment should be such as to comply in all respects with the requirements of the Home Office Regulations. The medium voltage compartment should be fitted with an insulated operating stand (wood) to comply with Home Office Regulation No. 23, the stand being hinged so that when not in use it can be folded inside the kiosk. When medium

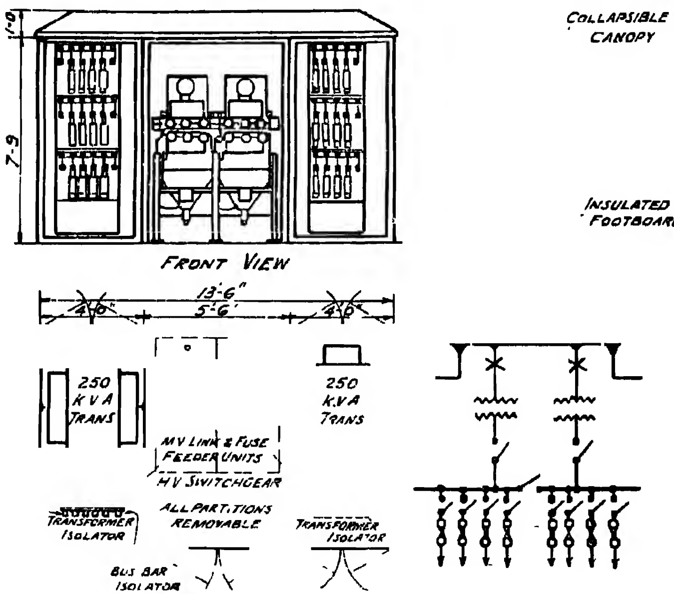


FIG. 41. Kiosk type sub-station.

voltage networks are interconnected, it is essential to include a triple-pole isolating switch or link between the M.V. busbars and the main transformer, thereby ensuring that the sub-station can be isolated from the M.V. network. If this precaution is not taken it is possible for an operator to commence work on the higher voltage side with a back feed from the M.V. network. Ventilation and heating are of importance, and if neglected may lead to continued trouble.

The question of local amenities may have to be considered, especially in residential districts, and transformer hum may give cause for com-

plaint. A brick building absorbs much of the noise associated with this hum, whereas a steel kiosk tends to amplify it. In urban areas brick buildings are often preferred even to steel kiosks because of price

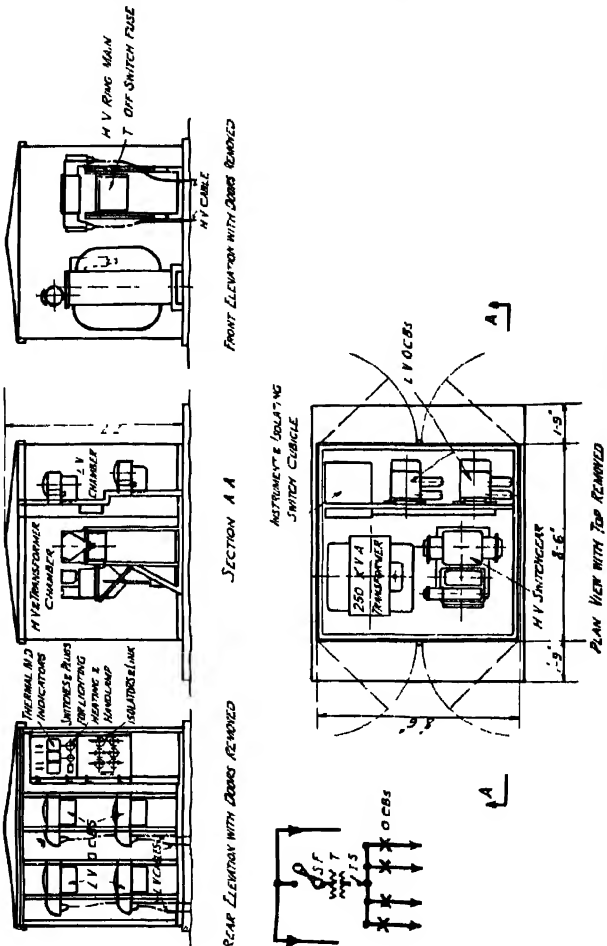


FIG. 42. Kiosk type sub-station.

level and amenity value and precast concrete has also been considered. An attempt has also been made to have designs of sub-stations approved by the Arts Council so that local licensing authorities can then have little or no objection to accepting one of the types in their localities.

Fig. 44 gives the main connections for one type of kiosk sub-station. The higher voltage isolators are arranged in one straight line and operated from outside by a handle fitted to the spindle controlling each triple-pole set. The connections permit of the following :

(1) Ring main can be broken at any sub-station, and the circuit breaker isolated.

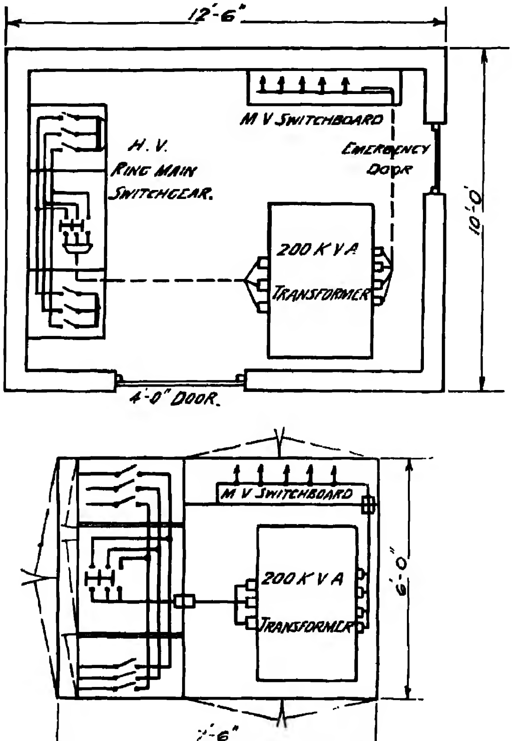


FIG. 43. Comparison between brick building and sheet steel kiosk.

(2) Ring main can be connected solid, and the circuit breaker isolated for inspection and maintenance.

(3) Transformer can be supplied from either side of the broken ring without the need for interrupting supply.

(4) Transformer can be isolated without interfering with the ring.

(5) Any one section of ring main—overhead line or cable—may be made " dead " with all transformers maintaining a supply.

An additional kiosk can be installed either by breaking the ring or by inserting three sets of isolators. The fuse has an inverse time-limit action and is so rapid with a short-circuit on the medium voltage side that it clears before the circuit breaker. On the medium voltage side the secondaries are connected to a link-board where portable instruments can be inserted. The neutral is of the same size as the phases to avoid voltage troubles with unbalanced loading.

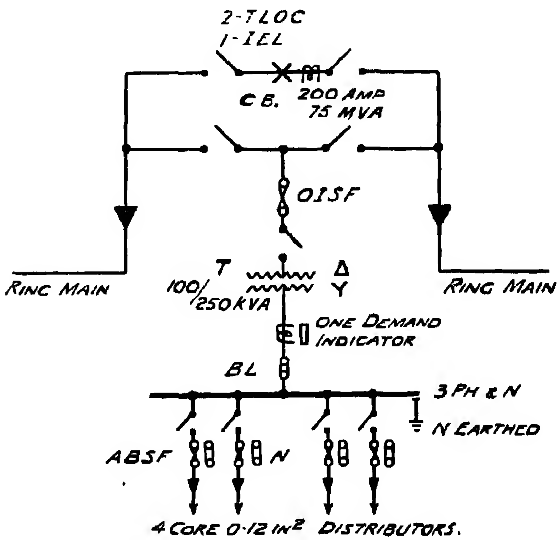


FIG. 44. Kiosk sub-station connections.

Special Type Kiosk. This is a precast slab structure of good appearance, Fig. 45. It consists of separate cells with sides and back of concrete, the fronts being the access doors, erected on a concrete raft with cable pipes and pits incorporated. Various layouts are possible and the design can be easily adapted to suit local requirements and extensions are possible. The supporting slabs are of three main types, the end, the intermediate and the transverse ; in addition there are special roof slabs. All except the small intermediate slabs are reinforced with ⅜ in. bars and fabric, the small intermediate slabs having ¼ in. bars. A cover of ½ in. is specified and the concrete mix is

1 : 2 : 4. All slabs are supplied with insulator holes and bolt-holes included and reference numbers cast on. Precast concrete cable pits are used so that the cable boxes can be mounted in a low position. The doors are of $\frac{1}{8}$ in. steel plate on a small channel-section framework, the whole being hinged to an angle-section frame which is bolted to the slabs Internal safety screens are fixed to the same frame behind and independent of the door itself. Louvre ventilators are included in the transformer chamber door, and a louvre ventilator is used in place of one of the small transverse slabs at the rear of the chamber. Over

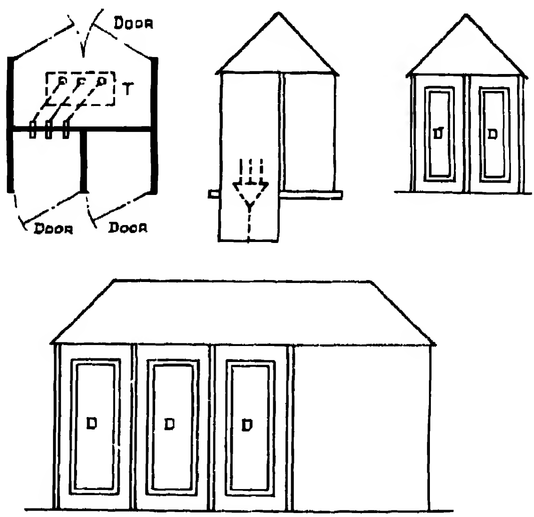


FIG. 45. Precast Concrete Slab Kiosk.

the concrete roof slabs is fitted a prefabricated wood roof structure covered with tiles or slates, where not considered necessary a waterproof finish is obtained by using asphalt. The advantages claimed for this type of kiosk are : cheapness, speed of erection, extended use of unskilled labour, good appearance, ease of extension and absence of condensation on inaccessible parts.

Pole-mounted or Overhead Sub-stations. One of the cheapest forms of sub-station, and one which does not involve any building work, is the pole type. ~~All the necessary~~ equipment is ~~mounted out-of-doors~~, being supported on one of the ~~poles carrying the line from which~~ the supply is taken. It is ~~necessary~~ to ~~adopt this~~ type of sub-station

with outdoor pole-mounting equipment, to keep within economical capital expenditure when catering for supplies of, say, 15 to 100 kVA having low revenue earning power over a rather long period.

Transformers ~~bolted or mounted on poles are used in capacities up~~ to several hundred kVA, and operating at voltages up to 33 kV. The transformer and associated control equipment should be such that the safety requirements of any regulations are complied with.

The most common type of overhead ~~equipment up~~ to about 100 kVA is the "H" pole (Figs. 46 and 47) with the transformer supported therefrom. In addition to serving as the sub-station, the "H" pole can be used as the terminal point of the overhead line. Under these conditions it pays to adopt horizontal strainers, thereby facilitating jumper leads and cutting down the overall length of the poles and consequently the cost.

For larger transformer units or groups of smaller units an elevated platform may be adopted, and such an arrangement eliminates the fencing required with the ground level layout. The ground rent or wayleave will only be that of one line pole, or, at the most, three poles, if fencing can be eliminated. This may be necessary if live metal is at a dangerous height from ground level. The capacity of a pole-mounted sub-station is limited by mechanical considerations and is largely a question of transformer size and weight versus pole strength. Transformers from 10 to 100 kVA (11 kV) inclusive are frequently mounted on a single stout wood pole. The 11 kV fuses are of the ground-operated withdrawable type, the operating pole being a hollow spar construction in three sections, one of the couplings being an insulator, the other being of metal and earthed. The transformer is supported by angle brackets, the fuses being carried by an angle structure which also serves as an anchoring point for the chain blocks to hoist the transformer. The M.V. switchgear and metering equipment are accommodated in a wood cabinet bolted to the pole (clear of the ground) with pitched roof and weatherboard construction, to house switch-fuses for two three-phase feeders. On a single-phase or individual supply point with overhead service line a smaller steel plate container is used for housing the fuses and in each case the operating pole is placed in this cabinet. The connections down the pole are of single taped and braided rubber-insulated cables carried on porcelain cleats, and taken through porcelain insulators into the cabinet at a height of about 8 ft. 6 in. to prevent interference. No troubles have been experienced with pole breakage or splitting due to the weight of the

transformers (100 kVA–23 cwt.). For 200 kVA units an H-pole is used with the transformer mounted on steelwork between the limbs, and 11 kV protection is by triple-pole liquid fuses. To replace a 100

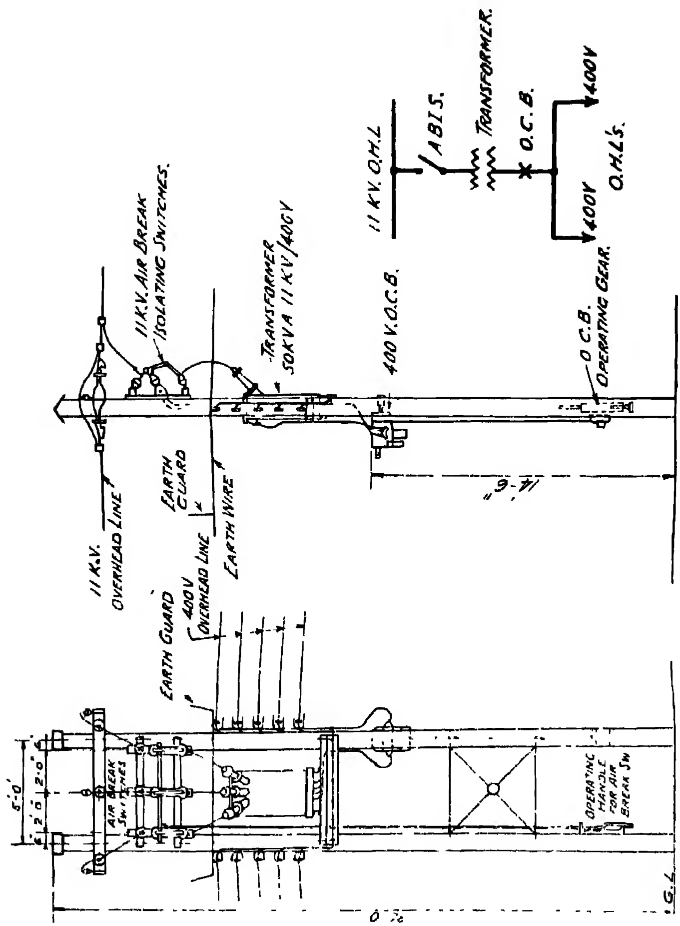


FIG. 46. Pole type sub-station.

kVA unit by one of 200 kVA can be dealt with by the erection of a new H-pole behind the single-pole termination, the complete equipping of the H-pole and changeover of circuits being done at a convenient time. The 11 kV fuses used are :

4 A for 10 kVA single-phase and 25 kVA three-phase.

10 A for 25 kVA single-phase and 50 kVA three-phase.

15 A for 100 kVA three-phase.

Some engineers have specified that transformers up to 50 kVA should be mounted on single poles and that units above 100 kVA should be mounted at ground level.

It is found that 11 kV transformers can be used with hanger brackets for ratings up to about 50 kVA three-phase, but for higher ratings (up to 100 kVA) a supporting platform may be desirable. For 22 and

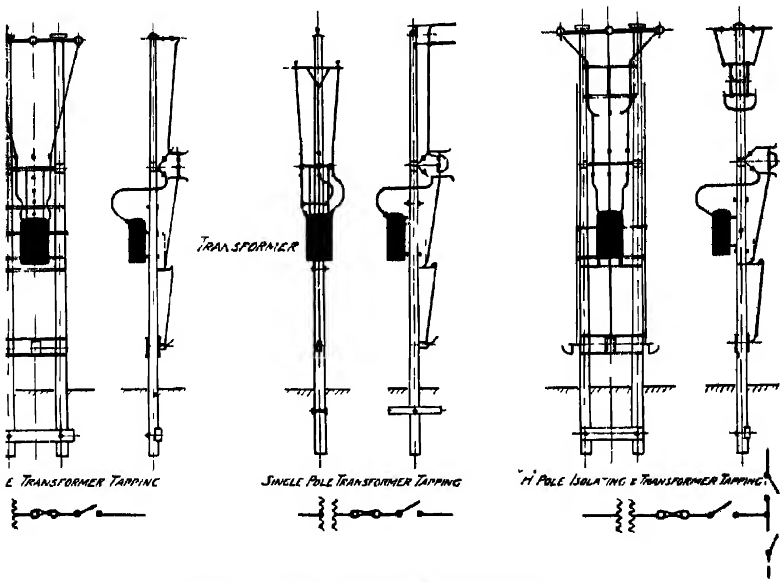


FIG. 47. 11 kV pole-mounted sub-station.

33 kV, a 25 kVA three-phase unit may be platform-mounted or arranged with hanger brackets. These figures are based on the assumption that either single or " H " poles are used, but given a three- or four-member structure with suitable platform, then larger units can be used with safety Pole-mounted equipments have been considered not to come within the Factories Act, and whilst there are many which leave no doubt, there is a degree of uncertainty in connection with the smaller type. These equipments are under the Act if they are " premises " for purposes of the electrical station, and the point can only be decided by a court of law. In general, the feature in

which many pole equipments would fail to satisfy the regulations is in the assembly of an isolating switch with a fuse as one unit, without the interposition of a screen. Fig. 48 shows a typical diagram of connections.

Mining Sub-stations. The sub-stations already outlined, with the

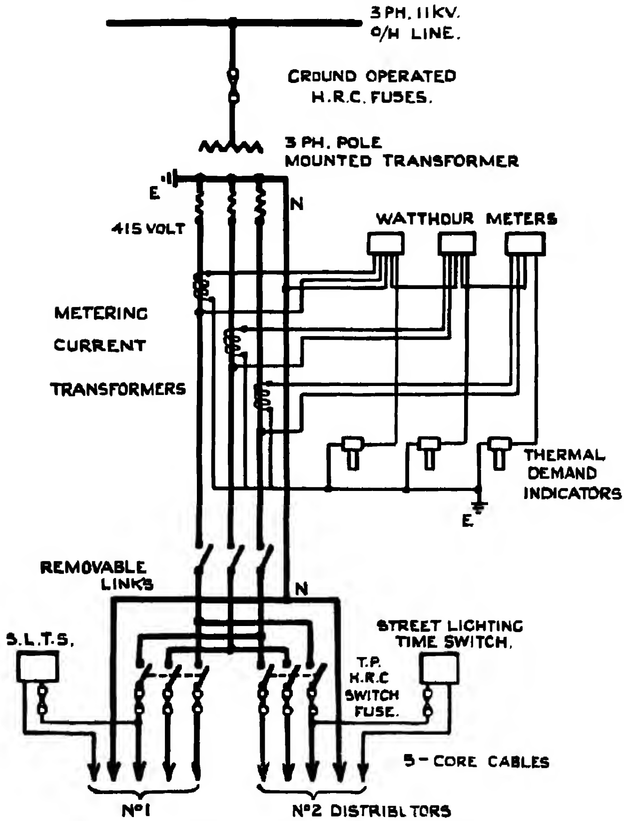


FIG. 48. Pole-mounted sub-station connections.

exception of those for cinematograph service, may be found in coal mining practice and will have to comply with the appropriate regulations. An example of a recent colliery installation will give some idea of the plant layout adopted for affording the main supply. The supply to the colliery is taken from the Electricity Board, but pro-

vision is made for connection in emergencies to the National Coal Board's power station. Four feeders from a 22 kV double-circuit transmission ring are brought into a main sub-station at the colliery for control of supply and distribution of electricity. In this sub-station the supply is stepped down through two and ultimately three, 5,000 kVA, 22/6·6 kV transformers for the winders and shaft feeders, and through two 2,000 kVA transformers from 22/3·3 kV for surface distribution by direct radial feeders and ring main to three subsidiary sub-stations located respectively in the winder towers and the washery, where the voltage is further stepped down to 550 V for general small power surface requirements. The layout of the main sub-station is generally as shown in Fig. 49. All switchgear is of the metal-clad type and physical barriers are included between switchboards and sections of switchboards to minimise the effect of explosion and fire. The control room houses the control and protective gear panels for the remote operation of the twenty-two 6·6 and 3·3 kV switchboards. Emergency lighting and the supply for the closing and tripping of the circuit breakers is obtained from a 110 V battery. The transformers are housed in pens, situated along the outside walls of the sub-station. They are separated by fire walls and provided with oil soakage pits covered with gravel to reduce fire risks. Fire-fighting equipment is installed in the transformer chambers and the switchboard compartments. The normal surface and underground load without the winders is some 4,000 kW at an average power factor of 0·6–0·7 lagging. With the No. 1 shaft winders operating at unity power factor, with automatic excitation control, the average colliery power factor is raised to about 0·85. A further improvement is obtained from the No. 2 shaft winder, the motor-generating set driving motor of which is a duplicate of No. 1 shaft machines, but is only working at half load. The machine is operated on constant excitation and is loaded up with leading kVA to its maximum capacity, so that advantage of the spare capacity can be taken from a point of view of power factor improvement. This brings the power factor up to an average of 0·9 lagging. There is some 8,000 h.p. of synchronous plant available for power factor correction when maximum load is on the colliery, all of which is located adjacent to the point of supply. Any further correction is done by static condensers located as near as possible to low power factor plant, in order to reduce voltage drop and distribution losses. For further plant details of colliery installations see Vol. 3, *Electrical Engineering Practice*, Meares, Neale & Carr (Chapman & Hall, Ltd.).

The only type that calls for comment is that for underground service. There are two principal arrangements, (1) Fixed (Figs. 50–52), and (2) Portable.

Transforming stations of the first class should be of brick, reinforced concrete, or steel-plate construction, and have strong partitions or barrier walls between each transformer and each switchboard. Steel arches with concrete filling also provide good housing, whilst reinforced concrete props placed skin to skin form a suitable lining for smaller in-bye (near coal face) stations.

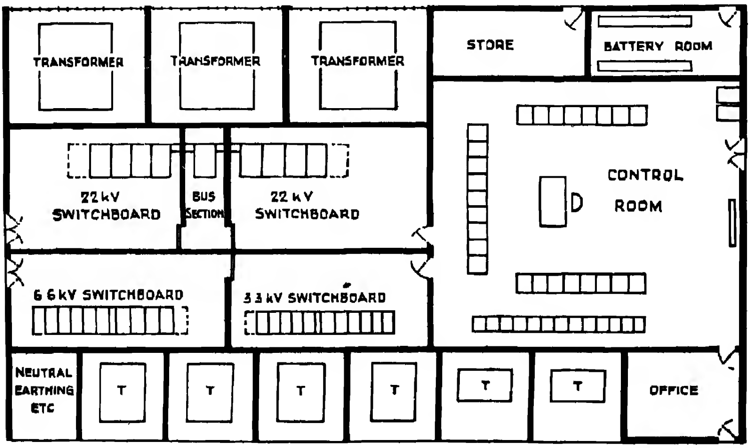


FIG. 49. Colliery sub-station layout.

Wherever possible, the sub-station should be made in a roadway slit between the main air intake and return (Fig. 53), so that in the event of a serious fire it is possible to divert ventilation into the return, thereby preventing miners working at the coal face being overcome by the fumes. A ventilation damper, of simple construction, is provided for controlling air flow.

Adequate ventilation and lighting are essential, and a transformer connected to the higher voltage busbar ensures lighting except in the event of failure of supply.

Fire-fighting equipment of adequate capacity to deal with fires likely to be encountered should also be provided. One method of guarding against the spread of fires is to include a well immediately

below each transformer and circuit breaker, into which the oil will drain. The wells are loosely filled with rubble (½-in. or larger) or part sand. In a transformer chamber the door would close with the wind or air current. Also on each side would be two 10 in. or 12 in. pipes through which normal ventilation passes. On the inner end of these pipes are fitted shutters between which the fusible link is in balance and connected by wire. Hand fire-fighting equipment, such as foam extinguishers, sand, etc., should also be provided and placed at the

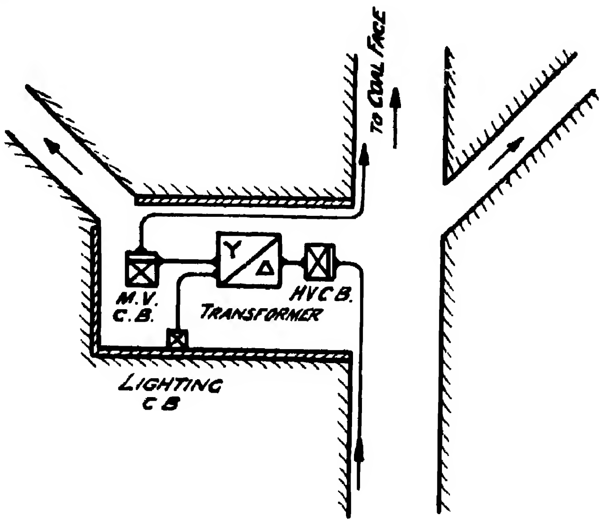


FIG. 50. Typical layout of mining (in-bye) sub-station.

entrance to the sub-station chamber so as to be at hand in case of emergency.

Expanded metal gates or screens, fitted with locks, to ensure non-interference by unauthorised persons, should be provided, as they do not impede air flow. Where a number of transformers and switchboards have to be housed and each group is in a separate compartment, it is necessary to include an emergency exit.

Portable type sub-stations are used when a lower voltage supply of reasonable capacity is required to serve a specific district. The principal features of this type are that it should be mobile, robust and as simple as possible.

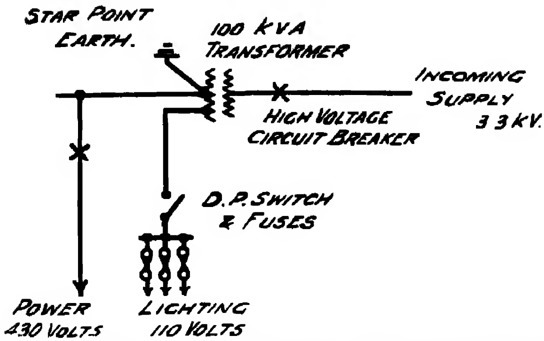


FIG. 51. Diagram of connections of mining (in-bye) sub-station.

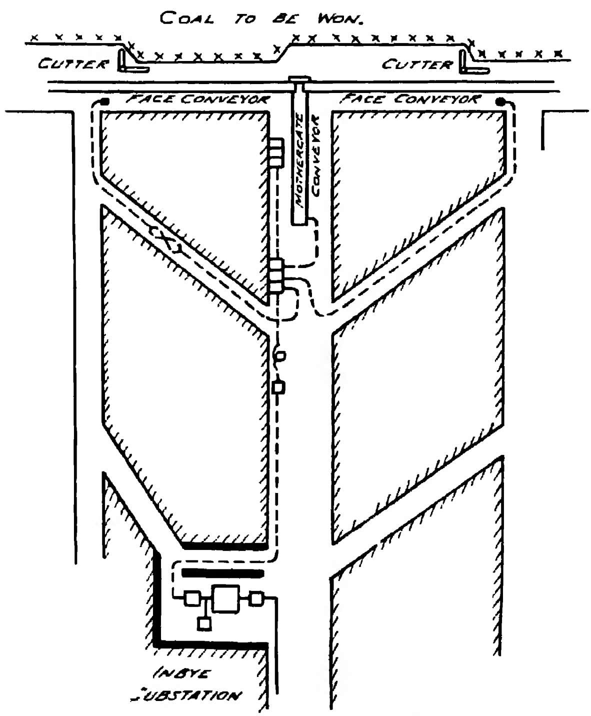


FIG. 52. Layout of double face unit.

The incoming and outgoing circuit breakers are mounted as one unit with the transformer. A standard arrangement consists of :

Transformer (underground mining type).

High voltage circuit breaker (flameproof, fitted with three over-current trips and double rate time lags and incoming cable box).

Medium voltage circuit breaker (flameproof, with two over-current trips with double rate time lags, direct acting earth leakage trip, ammeter and possibly voltmeter, also outgoing cable box).

Portable transformer units are advocated where the voltage drop in feeder cables is likely to be excessive resulting in overheating of cables and motors.

Mobile Sub-stations. This type has been developed to provide a temporary supply during constructional works, for repair work on ships in dock, and on failure of an important sub-station. The equipments vary according to the requirements of the electrical systems on which they are to function, but both A.C. and D.C. can be made available. The units are of weatherproof construction, which enables them to be stored or operated without the need for housing. Their mobility is such that one unit can serve as a stand-by to many others and this has advantages over the present practice of installing reserve plant in each sub-station, although the latter arrangement does provide for growth of load.

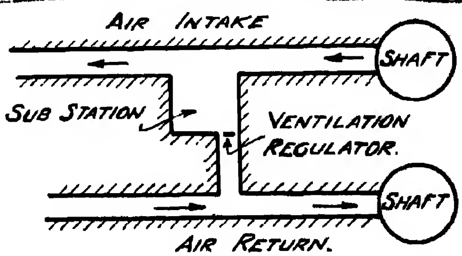


FIG. 53. Position of mining sub-station to air circuit.

These units proved invaluable where sub-stations were destroyed by enemy action, for a sub-station was replaced immediately by a mobile unit. The application of the mobile rectifier sub-station to railway and trolley-bus systems is worthy of note, and, apart from its usefulness in war, may prove to be equally useful under peace-time conditions. The total cost of conversion plant may be reduced by having a number of mobile sub-stations which may be shunted into sidings at the normal sub-station sites. They can be connected up to augment the supply or, alternatively, to permit of repair to plant which has failed, without interruption of services. A number of units to augment the normal sub-stations is a convenient and economical

method of dealing with such operating conditions. The electrical equipment for a railway service unit comprises the A.C. incoming switchgear, transformer, rectifier (six- or twelve-phase) of the air-cooled-steel tank pumpless type, and the D.C. switchgear. A rotary balancer can be included if three-wire D.C. supplies are required.

Mobile sub-stations can be arranged for both road and rail transport, since the overall sizes are all within the prescribed limits. The convenient length for road trailers is somewhat less than 20 ft., and if this is insufficient, the equipment may be sectionalised and housed in two vehicles. Ventilation problems have to be overcome, and if louvres and grilles are provided then due care must be taken to prevent ingress of driving rain and snow. Rectifier units of from 100 to 1,000 kW have been built and found satisfactory.

Factory Erected or Package Sub-stations. This method of purchasing sub-stations reduces the engineering work required since a single set of brief specifications outlining functional requirements is all that need accompany an order. Ordering all equipment from one manufacturer further reduces the engineering time required. It places on the manufacturer the responsibility of co-ordinating all of the various items of equipment, and supplying a workable sub-station complete with installation, overall arrangement and overall connection diagrams and drawings. It frees the supply engineer from the details of co-ordinating and expediting and makes his time available for system planning.

Automatic versus Manual Operation. The advantages of automatic operation for sub-stations may be briefly summarised as follows :

(1) No operatives required.
(2) Capital costs are reduced.
(3) Better protection is afforded.
(4) Maintenance charges are reduced.
(5) Distribution voltage is improved.
(6) Better use of feeder copper.
(7) Light load losses are reduced.
(8) Electrolysis trouble is minimised.
(9) Reduced noise.

Dealing with these in turn, the more outstanding features are outlined.

(1) There is a consequent reduction in labour charges and in faults during operation or whilst being put into service.

The sub-stations may be planned without consideration for

operators, since inspection and maintenance would only entail, say, two or three visits per week.

(2) Although the initial cost of the automatic sub-station is higher, if the costs are capitalised over a number of years it will be found that the extra cost is usually offset by the saving in labour charges.

For a single unit station there is little to choose from the point of view of building costs, but on increasing the number of units the balance would be in favour of the manually operated station. As the number of units is further increased the advantage of automatic operation diminishes, so that when three units are reached there would be little to choose. A separate automatic equipment is required for each unit, whereas no further increase in operatives would be necessary for a manually operated station.

(3) Protection is afforded against starting up against faults in the plant and duplicate protective devices become operative before a machine has approached speed.

(4) Maintenance is lower once the plant has got through the usual "teething" troubles.

(5) The cost of automatic stations being almost proportional to the number of units, it is desirable to keep the units per station to an economical minimum and dispose of them in the vicinity of the electrical loads on the systems supplied. In this way, the lower voltage loss is reduced with but little change on the higher voltage side.

(6) The more the units are sub-divided, and the more perfect the allocation at the electrical load-centres, the more usefully employed will be the feeder cables. If installed on a current carrying capacity basis, which is the general practice, the saving will be proportional to the station plant capacity.

(7) The reduction of light load losses to a minimum depends chiefly on the system served, particularly with regard to the time schedule on traction supplies. In many cases it may prove more economical to run the units continuously.

(8) The more automatic stations installed, the greater the number of feeding points and proportionally less capacity at each point, with consequent reduction in electrolytic action.

(9) Sub-stations being normally situated in populated areas require means to avoid nuisance from noise caused by high-speed rotary plant. This may be overcome by eliminating windows and providing specially constructed doors. Rectifiers are almost immune from this trouble.

Automatic control of isolated stations has one serious drawback,

in that delays may be occasioned in the event of failure of the automatic equipment, when considerable time may be lost in getting an attendant on site. To overcome this, it may be necessary to adopt a system of centralised control, entailing pilot cables.

Bibliography

W. C. BEXON. "Methods and Capital Costs of Distribution over an Extensive Area," *Proceedings I.M.E.A.*, 1927.

T. H. CARR. "Factory Sub-stations," *Power and Works Engineer*, April, 1941.

W. A. COATES and H. PEARCE. "The Switchgear Handbook," Vol. 2. (Pitman.)

H. COTTON. "Mining Electrical Engineering." (Chapman & Hall.)

J. L. FERNS and L. HEATON. "A Standardised Range of A.C. Sub-stations," *The Electrical Power Engineer*, March, 1945.

L. H. FULLER and C. R. CLARKE. "Sub-stations, with Particular Reference to Yorkshire Practice," *J.I.E.E.*, Vol. 96, June, 1949.

R. W. GREGORY. "Sub-station Design," *Proceedings of Conference on High Tension Systems*, Paris, June, 1925.

J. B. HORSLEY. "Electricity in Mines," *Journal I.E.E.*, Vol. 69, 1931.

F. J. LANE. "The Rotary Convertor Automatic Sub-station," *Journal I.E.E.*, Vol. 65, 1927.

C. W. MARSHALL. "The Lower Voltage Section of the British Grid System," *Journal I.E.E.*, Vol. 74, 1934.

J. W. MEARES, R. E. NEALE and T. H. CARR. "Electrical Engineering Practice" (3 Vols.). (Chapman & Hall.)

P. J. ROBINSON and E. L. MORLAND. "Some Practical Aspects of Electricity Development and Distribution," *Proceedings I.M.E.A.*, 1939.

E. SEDDON and J. ECCLES. "The Design, Equipment and Operation of Static Sub-stations," *Proceedings I.M.E.A.*, 1933.

T. H. TAYLOR. "Standard Sub-station Practice in Rural Electricity Supply," *Distribution of Electricity*, January, 1947.

N. THORNTON. "The Design of Static Sub-stations with some Notes on their Equipment," *Journal Junior I.E.*, October, 1924.

JOHNSTONE WRIGHT and C. W. MARSHALL. "The Construction of the 'Grid' Transmission System in Great Britain," *Journal I.E.E.*, Vol. 68, 1930.

CHAPTER III

CONSTRUCTIONAL WORKS

THE procedure in detailed design will depend to a large extent upon the type of station proposed, but the major items, apart from equipment, which will generally be common to all types, may be broadly summarised as :

(1) Foundations.
(2) Buildings.
(3) Supporting Structures.
(4) Outdoor Equipment Materials.
(5) Access.

Foundations. An examination of the proposed site will be made to ascertain its suitability for the erection of a sub-station. Where the choice of site is limited and excavations indicate unsatisfactory conditions, that is, the site is very poor for the purpose of foundations —particularly if large transformers have to be installed, then piling will have to be resorted to. Drainage must be considered, for water is always a source of trouble. The site area required will depend on the amount and type of plant to be accommodated, Tables 5 and 6.

The nature of the ground may be known to be sound locally by the stability of existing or previous buildings. The design and type of foundations will depend primarily on the sub-soil obtaining on the site, and the latter may, in turn, determine the building construction to be adopted. If the sub-soil has very poor load-carrying abilities, then a very light form of building will be adopted to keep the loading within the necessary limits. Foundations for machinery and structures must fulfil some or all of the following requirements :

(*a*) Maintain them rigid and keep all parts in true alignment.

(*b*) Transmit the dead weight of the machinery and structures to the ground and distribute it in such a way that the safe bearing pressure of the ground is not exceeded. This dead load always acts vertically downwards.

(*c*) Transmit, if necessary, the live loads to the ground. The directions in which the forces act will depend upon the types of machinery and structures.

TABLE 5. *Sub-station Data (Static Transforming Stations)*

Station	Total building capacity, cu. ft.	Cost per cu. ft., pence	Site area, sq. yds.	Year built	Building construction	Remarks (All flat roofs)
A1	14,460	13·80	225	1928	Exterior in wallstones with Ashler dressings. Pressed brick interior.	Indoor transformers.
B1	20,400	14·10	500	1932	Exterior in wallstones with precast stone dressings. Pressed brick interior.	Indoor transformers. Suspended floors, 6ft. high basement. Damp-proofed. Site of filled in cellars.
C1	10,613	14·60	396	1936	Exterior wallstones with precast stone dressings. Pressed brick interior.	Indoor transformers. Includes £96 for site enclosure.
D1	19,000	10·48	256	1938	Exterior and interior in pressed bricks.	Outdoor transformers.
E1	18,300	10·10	178	1938	Exterior in wallstones: pressed brick interior.	Outdoor transformers.
F1	13,040	16·10	352	1939	Exterior in wallstones with precast stone dressings. Pressed brick interior.	Outdoor transformers. Building built on reinforced concrete raft 18 in. thick owing to poor ground (ashes).
G1	5,900	17·50	208	1940	Exterior and interior in pressed bricks.	Outdoor transformers. Large amount of excavation to reduce site to road level.
H1	17,160	19·93	543	1941	Exterior in wallstones with precast stone dressings. Pressed brick interior.	Outdoor transformers. High cost due to increase in wages and boundary wall £220 called for in conveyance.
I1	2,720	26·50	120	1942	11-in. cavity common brick walls, exterior face pebble-dashed. Interior face flush-pointed for limewash.	Indoor transformer. Labour and materials increases.
J1	2,063	29·00	611	1942	Exterior in wallstones with precast stone dressings. Common brick flush-pointed limewash to interior face.	Outdoor transformer.

N.B.—All walling in three parts sand and one part cement.
Interior faces in best seconds facing bricks.
Sand lime bricks used in some chambers to give lighter effect.
Red facing bricks about 6*s*. per super yard extra over common bricks.
Sand lime white facing bricks about 5*s*. per super yard extra over common bricks.
Common hammer dressed wallstones (local product) about 9*s*. per super yard extra over common bricks (price in 1938).

TABLE 6. *Sub-Station Data*

Station	Plant capacity	Total building capacity, cu. ft.	Cost per cu. ft., pence	Site area, sq. yds	Year built	Primary voltage, kV.	Remarks
*a*1	1,500 kW. 2– 750 kVA.	48,700	11·33	700	1939	6 6	Traction. 550-v. D.C. General supply. 400-v. A.C. Outdoor transformers.
*b*1	1,000 kW.	54,000	10·80	1,130	1929	6·6	Traction. 550-v. D.C. Space for future general supply.
*c*1	460 kW.	6,180	15·22	800	1932	6 6	Traction. 500-v. D.C. Includes road making.
*d*1	700 kW.	10,580	15·00	544	1934	6·6	Traction. 500-v. D.C.
*e*1	2– 7,500 kVA. 1,210 kW. 2– 1,000 kVA.	71,220 29,000 61,700	13·10 8·57 12·48	2,679	1924 1938 1938	6·6 33	Traction. 500-v. D.C. General supply. 400-v. A.C. Outdoor transformers. 33 kV. switchgear (61,700).
*f*1	2–10,000 kVA. 1,000 kW. 2– 1,000 kVA.	34,755 75,000	14·13 15·74	1,118	1928 1938	6·6 33	Building completed in 28 days (14·13). 33 kV. switch house, including four transformer rafts, road making and site fencing. Outdoor transformers. Traction. 500-v. D.C. General supply. 400-v. A.C.
*g*1	1,000 kW. 2– 1,000 kVA.	51,600 24,780 43,000	12·0 14·46 10·44	916	1912 1925 1935	6·6	Traction. 500-v. D.C. General supply. 400-v. A.C.

TABLE 7. *Safe-bearing Loads on Sub-soils and Foundation Materials*

	Maximum safe pressure in tons per sq. ft.
Sub-soils.	
Alluvial soil and quicksand	Less than $\frac{1}{4}$
Chalk—Soft	$\frac{3}{4}$
„ Hard	3
Sand—Dry	1
„ Fine and very compact	3
„ Firm, enclosed by sheet piling	6
Clay—Moist, soft	$\frac{3}{4}$
„ Yellow, dry	2
„ London blue	4
„ Boulder, dry in thick beds	5
„ Wet in thin layers inclined	0
Gravel—Ordinary	3
„ Compact	4
Rock—Soft sandstone, limestone, etc.	2
„ Medium, Yorkstone, Gritstone, Blue limestone	8
„ Hard in thick layers—granite, etc.	30–75
Materials.	
Granite	20–30
Limestone	15–20
Sandstone	12–15
Portland stone	12–20
Blue brick in cement mortar	12–15
Red brick in cement mortar	4–6
Red brick in ordinary mortar	2–3
Concrete 1 : 2 : 4	10
Concrete 1 : 3 : 6	6

(*d*) Absorb as far as possible any vibrations set up by the machinery, and so reduce vibration which may be transmitted to the surrounding ground.

The machinery foundations should be isolated from the building

foundations to reduce the transmission of vibrational forces to a minimum and obviate troubles due to settlement. A foundation

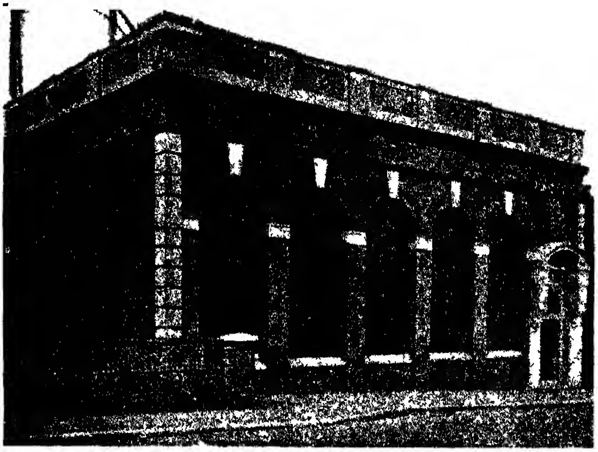


FIG. 54. Trolley-bus sub-station

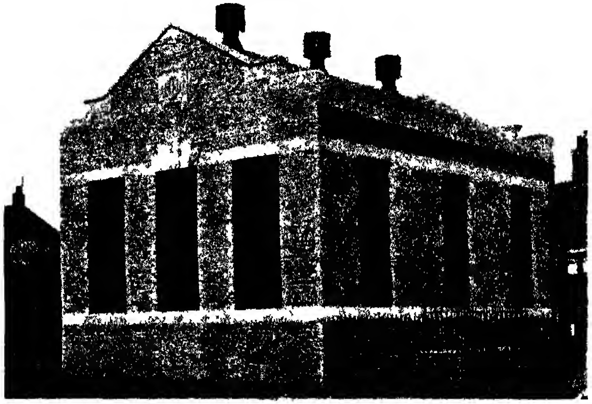


FIG. 55. Trolley-bus sub-station (Station f1—Table 6).

should be heavy enough to take care of any accidental out-of-balance which may arise during normal operation of the machinery. Table 7 gives safe-bearing loads for different sub-soils and materials.

There are three types of foundations, viz. (1) Rafts ; (2) Piers ; (3) Piles.

The first is used where the loading is concentrated at many different points, or where one load, *e.g.*, a transformer, is concentrated, and the

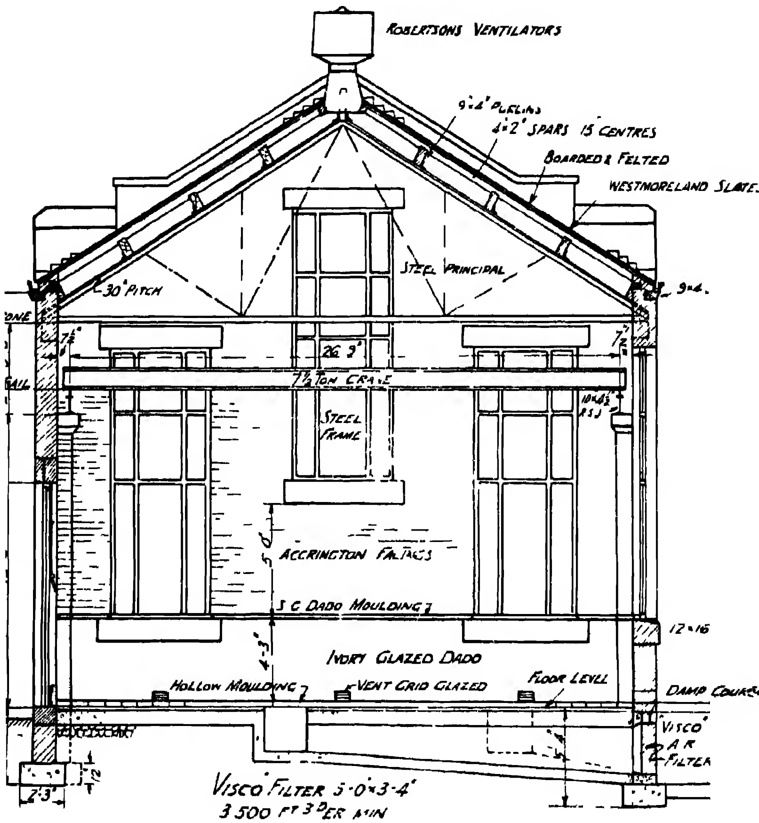


FIG. 56. Building details for Fig. 55.

ground will safely sustain the load. On made-up ground, such a construction ensures uniform settlement. Where the ground is incapable of taking a reasonable loading and a suitable condition is possible at from 5 to 15 ft., then piers can be used. The footings can be spread to maintain the piers within reasonable dimensions.

Piles are used where no ground is capable of sustaining the desired load within, say, 20 to 30 ft. of the surface.

Approximate depth to which foundations should be taken :

½ ton ft.²	— 1	ft.	minimum	depth
1 ,, ,,	— 2	,,	,,	,,
2 ,, ,,	— 3½	,,	,,	,,
3 ,, ,,	— 5	,,	,,	,,
4 ,, ,,	— 6½	,,	,,	,,

The effects of weather conditions must be kept in mind when determining the depth.

Buildings. The arrangement of the buildings housing the plant will primarily depend upon the site available and the ultimate capacity of the sub-station. The foundations and superstructure of all buildings are designed to comply with local Building Acts, and in some cases such requirements have entailed considerable additional expense. The selection of materials to be used in the construction of the buildings deserves careful thought, particularly if a new supply area is involved, and should be such that an economical but substantial structure is obtained. The primary function is to house the plant as cheaply as possible. Attempts are made to provide pleasing architectural features which lead to greater capital expenditure but in no way enhance the reliability of supply or reduce the running costs. The buildings should be soundly constructed in good quality materials, and designed to harmonise with the neighbouring buildings and amenities. The latter is a wise policy and fosters good feeling when sites are scarce in residential areas.

When seeking compulsory powers for the acquisition of sub-station sites, the fact of providing buildings of good design and appearance (Figs. 57 and 58) will create a favourable impression on the granting authorities and result in facilitating negotiations. The materials most commonly adopted are brick, stone and concrete, the classes depending chiefly on the localities in which the stations are built. Panelled brickwork, relieved with stone or imitation stone courses, and a reasonable proportion of glazing to provide good natural lighting, is often provided. Reinforced concrete has been used, and appears to be quite satisfactory both as a structure and from the point of view of cost, but care is needed if any decorative features are to be included. Patent glazing with wire-wove glass has also been

used in switch-house designs, and has the advantage of being a very light form of construction, cheap, quicker in erection, and provides excellent natural lighting.

The size of building depends upon the plant to be installed, but

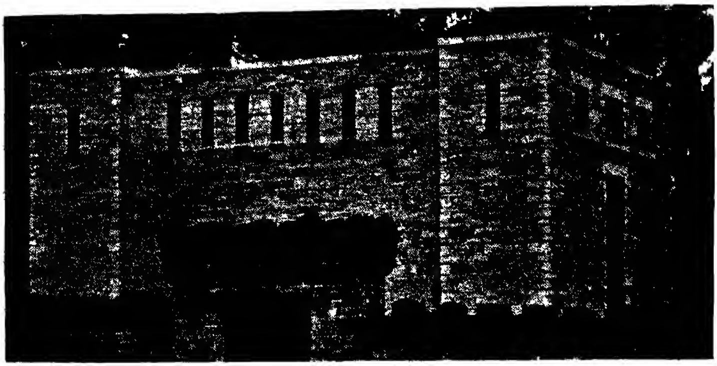


FIG 57. Trolley-bus sub-station containing transformer and D.C. switchgear 4–125 kW M A. rectifiers (glass bulb).

FIG. 58. Trolley-bus and general supply sub-station, containing transformer and D.C. switchgear. 4–125 kW M.A. rectifiers (glass bulb). Separate chambers for general supply transformer, H.V. switchgear and L.V. distribution units.

there must be ample room for persons to perform their duties of switching, inspection and maintenance safely and efficiently. Flat reinforced concrete roofs are to be preferred, as they are usually cheaper than the pitched type, and the maintenance charges lower. The appearance, however, is not too attractive, and in residential districts

some attention should be given to this aspect to ensure harmony with the surrounding architectural styles. Sub-stations for supplying domestic networks should, on account of their location, be designed to harmonise with surrounding property, and special features may be introduced to improve appearance. Buildings constructed of brick with stone facings in cement mortar and reinforced concrete make a substantial and permanent job (Figs. 59–68) and require a minimum of maintenance. The flat concrete roof is made waterproof by the application of asphalt or other water-proofing materials. The external

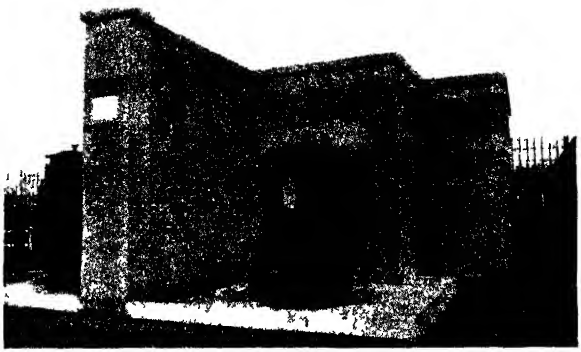


FIG. 59. Transforming station suitable for 2–1,500 kVA units (Station F1—Table 5).

appearance of brick buildings is improved by the use of a certain amount of artificial stone.

Buildings should be placed in clean and dry situations, otherwise repeated trouble may result from dust and damp. In industrial areas, and especially where sub-station chambers are on consumers' premises, it is sometimes difficult to obtain ideal conditions. The materials used in the construction should be sound, durable, and be fire and explosion proof, to protect the plant from consequential damage in the event of fire or explosion. Collapsing of roofs, walls and screens is thus minimised.

In one design the foundations of the external walls and trenches are laid in one operation, with a $4\frac{1}{2}$-in. brick externally, 2-in. filled cavity and a 9-in. internal wall all taken to floor level. A damp-course of two layers of Welsh slates is used. The 11-in. cavity wall com-

mences from the damp-course. The brickwork below floor level and inside the cavity walling is of selected common bricks.

In both flat and pitched roofs precast beams are used and one

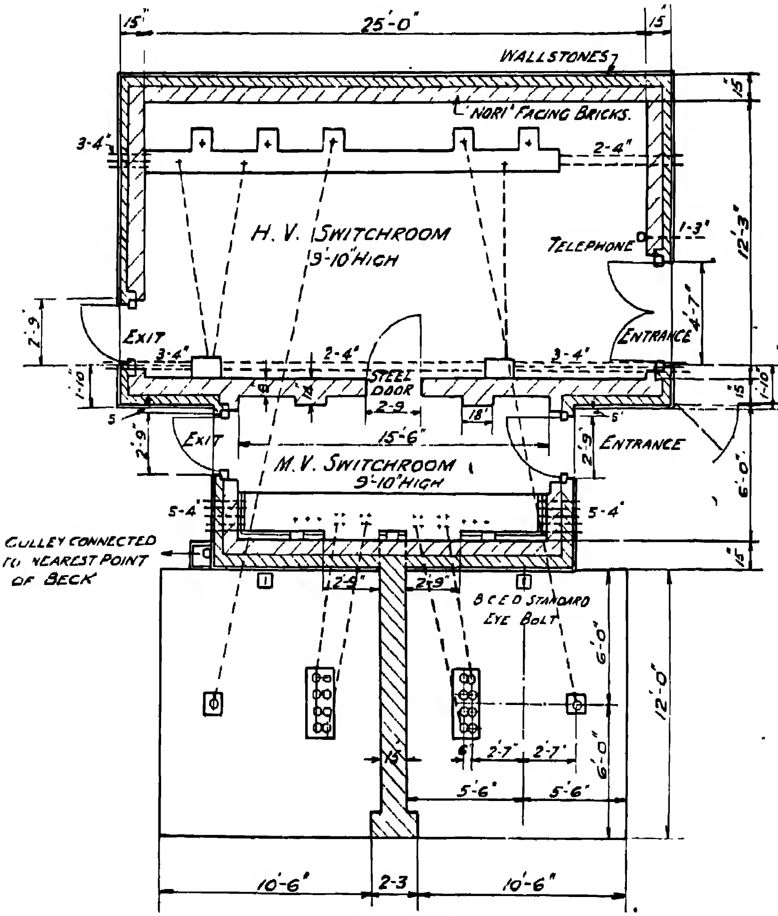


FIG. 60. Building details for Fig. 59.

supported on the inner 4½-in. brickwork and across the centre on a steel joist which is encased in concrete.

For a flat roof finish a cement screed is laid to fall to the outlets and this is covered by three layers of roofing felt (each layer lapped). The first layer is laid free from the concrete roof to allow for movement in

the precast beams, whilst the remaining layers are laid in bitumen. The pitched roof is constructed direct off the beams, two roof trusses being used and secured on wall plates. The tiling is laid on felt and battens.

Although it is almost impossible to standardise buildings, every effort should be made to regularise constructional details. Building designs can be standardised to a limited extent, especially if switchgear of the same type is adopted throughout the system for specified ratings. Sub-stations with slate or tiled roofs do not withstand the effects of blast and falling debris, and are rendered unfit to withstand the weather. Certain rectifier traction sub-stations have been constructed of prefabricated reinforced concrete panels, each 3 ft. wide, bolted together. The whole of the interior was sprayed with asbestos to give heat insulating properties. To prevent distortion in the event of fire, it is desirable that building steelwork should be encased in concrete. A steel frame building may be

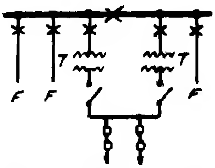


FIG. 61. Main connections for Fig. 59.

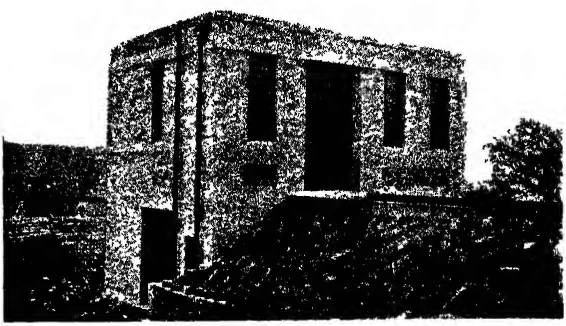


FIG. 62. Trolley-bus sub-station—2–350 kW auto G.B. rectifiers on upper floor and transformers on lower floor, three-phase 6·6 kV/500 V. D.C. (Station *d*1—Table 6).

made fire-resisting by affording such protection as will delay for a few hours the attainment of an injurious temperature. On more important stations it is preferable to use moulded asbestos protection as this does not disintegrate under the action of fierce or unevenly applied heat as concrete does and it is considerably lighter.

A roof thickness of 6 in., falling to 4 in., with ¾-in. asphalt covering

is usual for flat concrete roofs. For large chambers hollow steel beam construction has been used, the roof being finished off with a $\frac{7}{16}$-in. layer of insulating board and seven-ply patent felt roofing in bitumen.

The walls are either of hollow or solid construction, 13½, 11 or 9 in., subject to any local building by-laws. Outside, boundary and partition walls should have a damp-course of treated felt, or two courses of blue bricks. Where boundary or other walls adjoin the main building, a damp-course should be provided at the top. Cable should be weathered where they pass through outside walls, the slots being inclined and placed as high as possible. All holes in section walls for the passage of busbars and cables should be sealed.

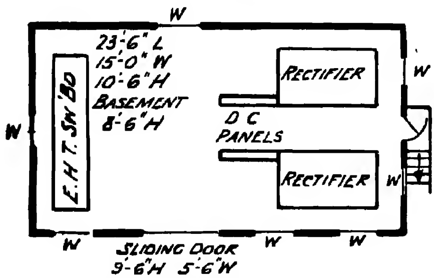


FIG. 63. Layout for Fig. 62.

In the more important sub-stations the floors should embody some form of oil drainage, for it is desirable that any oil which may be released through a circuit breaker tank or busbar chamber failing should be quickly drained from the room and so prevent spreading if on fire. Various methods are in use, some of which are :

(1) Arranging the floor to have a slight fall towards a longitudinal trench extending the entire length of the building ; the trench being filled with sand, pebbles or granite chips and covered with open grating.

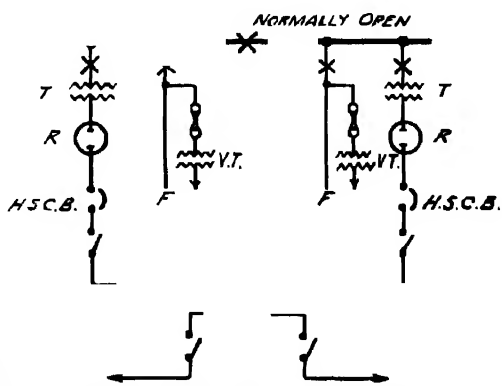


FIG. 64. Main connections for Fig. 62.

(2) Providing large chases in the floor directly below each circuit breaker, having adequate fall towards a longitudinal trench or sump outside the building. This may be further improved by filling the

trough with pebbles and then covering with open grid flooring. This has the advantage of reducing the temperature of the hot oil, and may actually reduce it below ignition point.

(3) Fitting a cast iron drain pipe in the floor below each circuit breaker and connecting it to a header pipe leading to an outside sump, the floor immediately below each breaker falling to the pipe in hopper formation.

Floors are 1- to 2-in. granolithic paving on 6-in. concrete for the main chambers, and 6-in. concrete for basements. The floors are rebated to take chequered plates over the trenches. Plate sizes can be standardised which facilitates ordering and reduces cutting away on site.

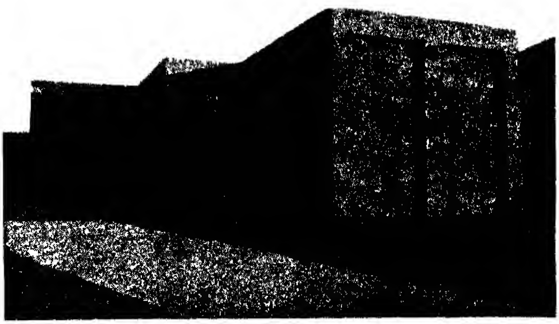


FIG. 65. Transforming station suitable for 2–1,500 kVA units. Exterior in wallstones with precast stone dressings. Pressed brick interior.

The channel supports over the trenches for taking the switchgear are set both for level and position and run solid with the floor finish. When designing switch-house floors allowance should be made for the worst possible loading conditions. For example, a three-phase (single tank) 33 kV, 750 M.V.A. oil circuit breaker weighs about 7 tons "dead" weight, but under fault conditions the equivalent "dead" weight may probably be in the region of 24 tons. This is a point of importance where basements are directly below switchboards (Fig. 69).

Windows are omitted wherever possible, especially in those stations situated in industrial areas, other forms of air pressure release being included. The chief objections are cleaning, stone-throwing and higher cost than brickwork. Armoured plate glass has been used, and although the cost is twice that of ordinary glass, it is practically

unbreakable. Wire-wove glass has also proved useful, for apart from guarding against stone-throwing, it offers fairly good resistance to fire. The glazing of the windows should be of 21-oz. glass with medium size panes, and the window frames should be free on the outside in order that they would give easily in the event of internal explosion. Where windows for pressure release must be included they should be of the internal type to be effective against external blast or splinters. A large proportion of the windows should be arranged to open outwards to release any air pressure in the building caused by ignition of explosive gases.

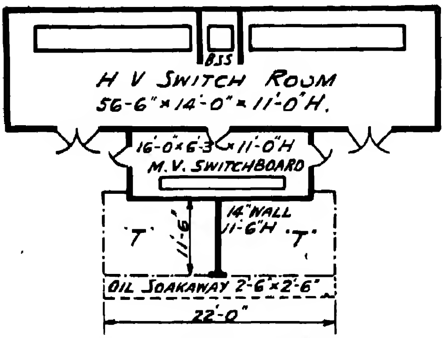


FIG. 66. Layout for Fig. 65.

Experience has shown that explosions are possible with comparatively small oil circuit breakers, and can cause considerable damage to buildings unless some form of safety valve is included. Adequate window space in the form of roof, or laylights, or, alternatively, side windows high up in the walls, are suitable. Windows in the side walls, placed above the level of the switchgear, reduce the possibility of

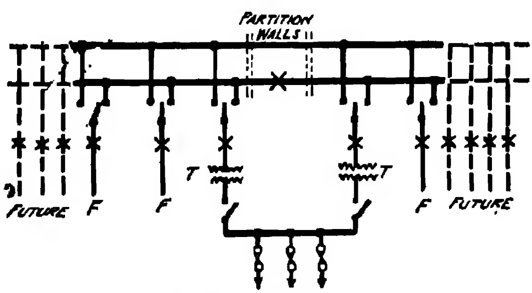


FIG. 67. Main connections for Fig. 65.

damage from bomb splinters or missiles. The windows can be of the fixed type, but certain sections should be hinged to swing outwards and be normally held closed by unlatched counterweights.

Some engineers include a number of windows as they provide a useful blow-out in the event of a circuit-breaker failure and may save the door.

All doors should open outwards and oil traps should be included at the thresholds of doors in division walls. Where a switch-house is divided into chambers and basements, each should have two exits. The emergency door should be placed at the opposite end to the main door and be arranged to open from the inside only, but be left unlocked. Very large doors should include a wicket door about 6 ft. 6 in. high by 2 ft. 9 in wide Roller shutters or sliding doors appear to be preferable for the larger openings, and should be fitted with operating gear which may be operated from both inside and outside. Doors 8 ft. high by 5 ft. wide provide normal access for personnel and transformers up to about 500 kVA capacity. Self-closing, fireproof doors

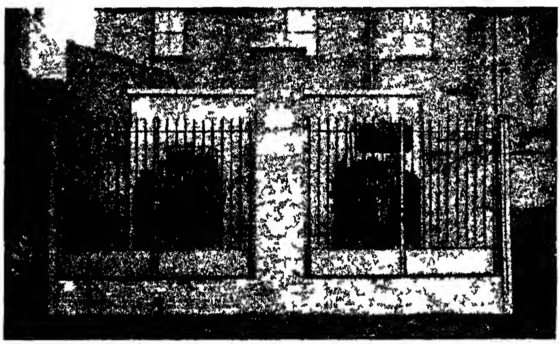


FIG. 68. Transforming station suitable for 2–1,500 kVA units (Station G1—Table 5).

of sound construction should be provided between any adjoining switchgear chambers. All doors should be of light steel or approved wood construction, the latter having proved more fire-resisting than sheet steel, although it is not so good as the modern fire-resisting doors which are usually expensive and only justified on the more important chambers.

A special safety screen may be provided inside a transformer chamber which is not opened with the transformer chamber door and serves as a check warning of live conductors. Rebates should be included in all doors to keep out storm water.

The leading out of the main cables often presents difficulties, and it is necessary to provide trenches, pits or basements to facilitate cabling. An alternative is a ramp (Fig. 70) at the rear of the switch-

gear, which is a simple method of ensuring isolation, since the cables are taken into the chamber through cable pipes to the individual circuit breakers and transformers. This is not always possible in industrial and densely populated areas, and the switchgear also affects the cabling arrangements. There has been a tendency to keep basements as small as possible and incorporate a pebble-filled oil well in the switch chamber

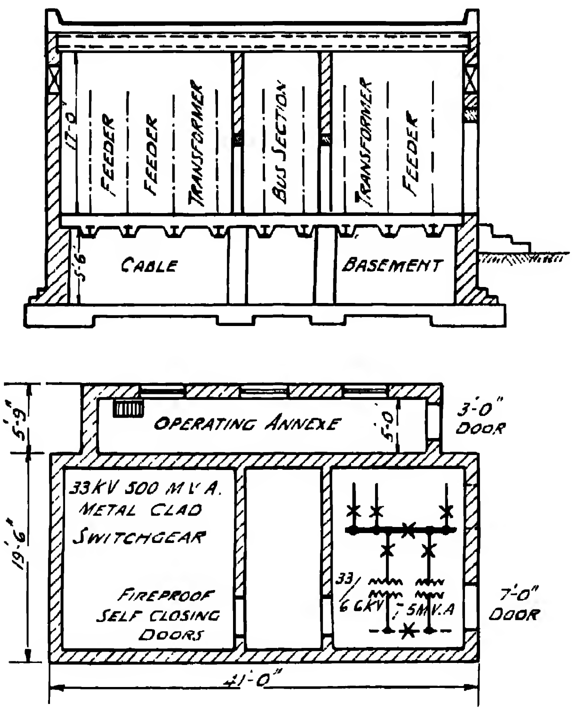


FIG. 69. 33 kV switch house.

floor. The cables are kept clear of the well, being separated by fireproof barriers, then taken into a small basement. Basements have been eliminated by placing the cables in pebble- or sand-filled trenches in the switch chamber. Switchgear may have cable boxes with horizontal entry and by suitable siting the cables enter and leave the building by holes in the panels along one side thus avoiding ducting or trenching in the floor. Holes in the switch chamber floor for the passage of cables and conduits into the basement should be sealed

to prevent the ingress and spreading of burning oil. It is desirable that basements and basement sub-stations should be drained. The Home Office Regulations recommend that sumps should not be connected to the town drainage system, as flooding may result due to water "backing up" the drain during heavy rains. There is also a risk of the trap becoming dry and the basement being filled with sewer gas. A manhole should be included to give the desired access for both personnel and plant.

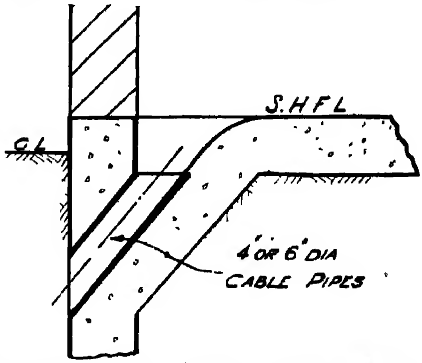


FIG. 70 Leading of cables into switchgear and transformers.

Buildings should provide adequate ventilation to carry off moisture condensing on the walls and plant, and more especially in the case of newly - constructed buildings to remove the moisture coming from the masonry. The maintenance of a constant temperature is desirable to prevent breathing and moisture condensation. Provision should be made for the free circulation of air over the whole of cellular, cubicle, and truck types of switchgear. The chief danger arises where a sub-station is built in a damp situation and is exposed to moist atmospheric conditions. A discharge may take place over the porcelain insulators, producing ionisation of the air and

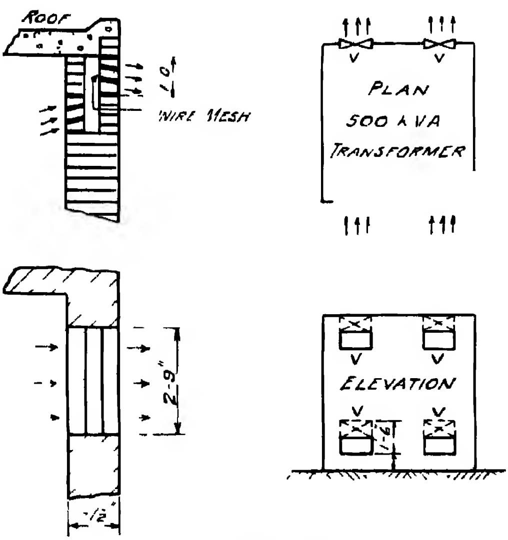


FIG. 71. Wall ventilator.

so reducing its dielectric strength. Consequently, when a transient occurs the resulting high-frequency currents can do damage by jumping over inches of ionised air gaps to earth, which may be followed

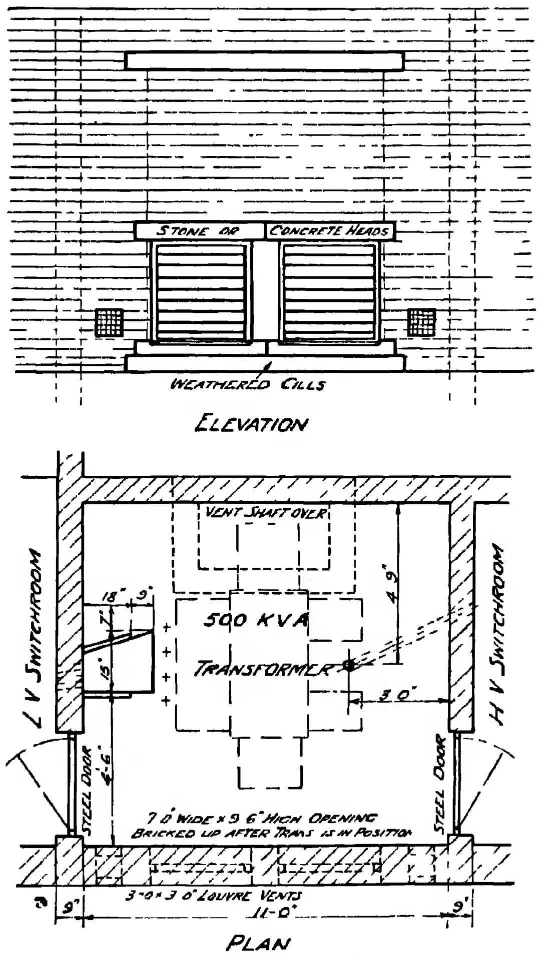


FIG. 72. Built-in transformer.

by the main arc. To ensure good ventilation, the inlets should be near the floor of the chamber, and the outlets near the roof at the opposite end if possible. If the registers are sufficiently large, the

heat given off by indoor transformers will usually maintain ample air movement. A suggested minimum sectional area of the inlet and outlet openings is 1 sq. in. for every 10 cu. ft. capacity of the chamber.

Another empirical rule which has been found satisfactory is :

12 ft.^{2} inlet area per 1,000 kVA installed 6 ft.^{2} outlet ,, ,, ,, ,,	Also see Chapter IX.

Before this was adopted, an inlet area of about 15 ft.^{2} was employed, but in most cases this proved to be too much.

One authority has quoted a figure of 100 to 150 ft.^{2} of air per minute per kW of transformer loss. Another authority has suggested $1\frac{1}{4}$ ft.^{2} of ventilator area per 100 kVA of transformer capacity. This rule is based on practical experience rather than theoretical considerations, but it is essential to have the inlet low at one end of the chamber with the outlet high up at the other end. The rule is not intended to

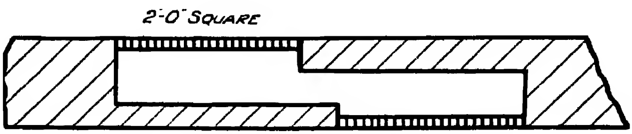


FIG. 73. Staggered wall inlet ventilator.

apply beyond 1,000 kVA capacity, and there appears to be no advantage in limiting the outlet area to half the inlet. The desideratum of a good ventilator is that it should effect a constantly changing air, have no moving parts and no running costs. The louvre types may be fitted with fire seals, which close when the seal breaks. Patent ventilators having no moving parts are obtainable, and appear to be satisfactory. They incorporate fins inside the casing in such a manner that any movement of air creates an upward suction. It is claimed that a down-draught is impossible even in stormy weather, and an up-draught is inevitable even on the calmest day.

Wall ventilators or air grates (Figs. 71–73) are also provided, and these should have fine mesh expanded metal or wire guards inside. Large grates should have an internal weathering wall or be staggered to stop the direct drive of rain or snow into the station, and also prevent access with sticks or wires. Sliding and hopper types of damper may be included to regulate the air inlet. An opening in the roof protected by a concrete slab supported at a height of about

2 ft. above roof level is also used. This opening can extend the full length of the chamber depending upon the installed transformer capacity. Pipes set in the roof (Fig. 74) and shielded from the weather by cast iron gratings also a precast concrete canopy with louvres (Fig. 75) are alternatives. Some transformer chambers are assumed to be designed on scientific lines by virtue of allowing for the maximum transformer losses and incorporating inlet and outlet ventilators, which depend very largely for their effective functioning on the direction of

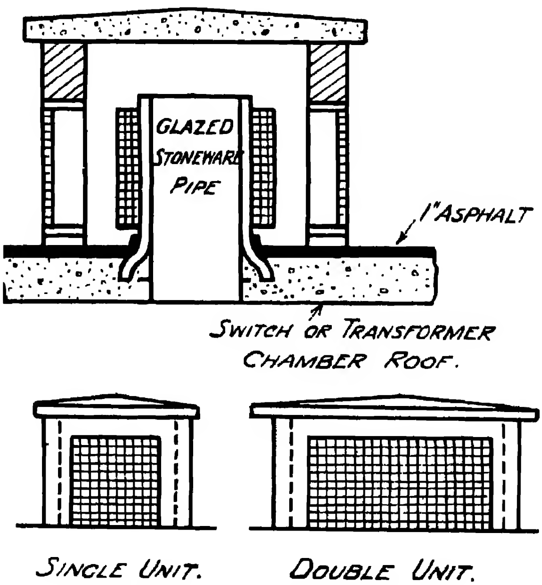


FIG. 74. Roof outlet ventilator.

the wind. It is found that the wind has a big effect on the temperature of the air surrounding an indoor transformer, and if full benefit is to be obtained adequate ventilation should be provided. Rectifier sub-stations should be adequately ventilated, and during winter months the temperature should be maintained at about 60° F. This is important where steel tank rectifiers are installed and the water cooling systems are to be frost-proof. Transformers placed indoors assist in maintaining the building temperature at a suitable value during cold periods, but impair cooling during summer months and

simultaneously prolonged heavy loading. Where a large sub-station is operating under such conditions and the temperature is unduly high, it is possible to open a door provided an expanded metal screen is fitted to prevent unauthorised access.

Exhaust fans are of little use and the best way is to install fans which force air into the building. In some large sub-stations the ventilating air is treated with a precipitating-type air filter as this keeps dust accumulation and therefore cleaning and maintenance on insulators to a minimum. Refrigeration can be used for cooling.

Where outdoor switchgear is installed it is necessary to provide a room for the control equipment, protective relays, instruments and

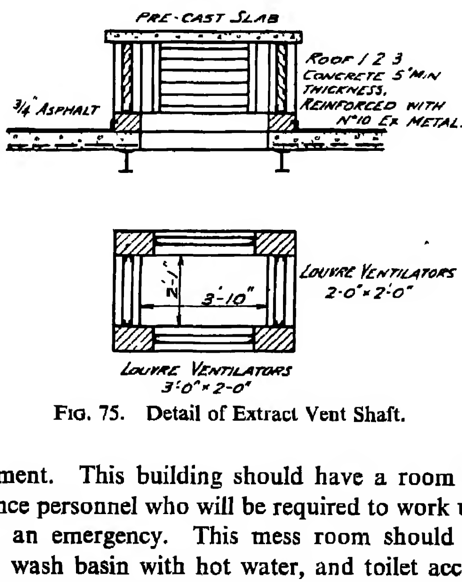


FIG. 75. Detail of Extract Vent Shaft.

testing equipment. This building should have a room set apart for the maintenance personnel who will be required to work under varying conditions in an emergency. This mess room should have a sink, small cooker, wash basin with hot water, and toilet accommodation. Attended sub-stations should also be provided with such facilities.

The maintenance required on a building is painting, whitewashing and pointing, which can be carried out without danger. Care must be exercised with medium voltage bare connections and open type switch and fuse boards. Accidents have occurred and it is advisable to see that effective screens are provided, or that an authorised person is present. Tables 8, 9 and 10 give further sub-station data.

Underground sub-station constructional details are given on Figs. 76–78.

TABLE 8. *Sub-station Building Data*

Station	Netbuilding capacity, cu. ft.	Cost per cu. ft., pence	Remarks
A2	4,600	14·0	
B2	5,600	12·8	
C2	6,000	14·6	Basement necessary due to site conditions.
D2	11,000	8·9	
E2	23,500	8·8	Glass bulb mercury arc rectifiers installed.
F2	23,500	9·3	Basement necessary due to site conditions.

Stations built 1936–37. Brick buildings with flat roofs.
Transformers out-of-doors. Industrial area.

TABLE 9. *Traction (Railway) Sub-station Data*

Location	Plant capacity	Net building capacity		Plant losses kW.	Cu. ft. per kW. loss	Type of plant installed
		Cu. ft.	Cu. ft./kW.			
India .	7,500	220,300	29·3	450	490	Rotary convertors.
	7,500	234,000	31·3	450	520	,,
South Africa	6,000	132,000	22·0	320	410	,,
	6,000	231,000	38·5	620	375	Motor generators.
Britain .	6,000	120,000	20·0	220	1,000	Rotary convertors.
	3,500	90,000	25·6	150	600	,,
	7,500	330,000	44·0	350	940	Steel tank mercury arc rectifiers. Air-cooled transformers in same building.
	8,000	235,000	29·4	210	1,110	Steel tank mercury arc rectifiers.

Note. The plant losses are only approximate.

TABLE 10. *Trolley-bus and Tramway Sub-station Data*

Station	Plant capacity, kW.	Net building capacity		Plant losses kW.	Cu. ft./kW. loss	Remarks
		cu. ft.	cu. ft./kW.			
*a*2	460	3,100	6·8	18	172	2 G.B.R. sets (2 bulbs per set). Transformers in basement.
*b*2	700	3,700	5·3	26	142	2 G.B.R. sets (2 bulbs per set). Transformers in basement.
*c*2	1,000	25,200	25·2	73	348	2 R.C. sets. Indoor transformers.
*d*2	1,000	39,000	39·0	25 G.B.R. 28 R.C. — 53	737	1 G.B.R. (4 bulbs). 1 R.C. Transformers in separate chamber.
*e*2	1,000	24,900	24·9	22 G.B.R. 36 R.C. — 58	426	1 G.B.R. (3 bulbs). Outdoor transformer. 1 R.C. with transformer.
*f*2	1,210	31,000	25·6	27 S.T.R. 28 R.C. — 55	554	1 S.T.R. 1 R.C. } Transformers in separate chamber.
*g*2	1,210	41,000	33·9	47 S.T.R. 40 M.C. — 87	472	1 S.T.R. 1 M.C. } All equipment in same building.
*h*2	1,800	14,000	7·8	66 S.T.R.	212	2 S.T.R. sets (2 tanks per set—pumpless). Outdoor transformers.

N.B.—Plant losses only include those in building mentioned. "G.B.R."—Glass Bulb Rectifier. "R.C."—Rotary Convertor. "S.T.R."—Steel Tank Rectifier. "M.C."—Motor Convertor.

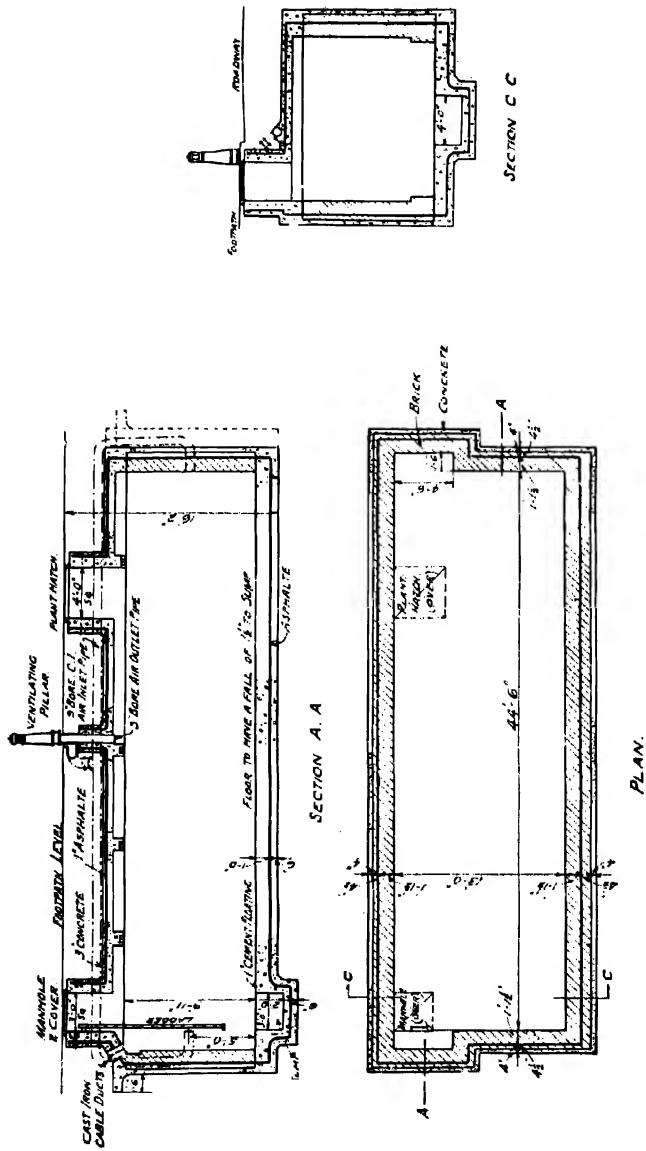


FIG. 76. Underground sub-station.

Outdoor type transformer sub-stations consisting of one 15 to 20 MVA unit have been provided in which protection is afforded by strongly built blast walls of reinforced concrete dressed with stone slabs. A net is stretched across the top and serves as a peace-time protection for the transformer. Reinforced concrete beams running in vertical guides are used instead of main doors, and gratings provided in front of the enclosure cover intake openings for cooling air. An access door for inspection and maintenance purposes is of heavy armour plate.

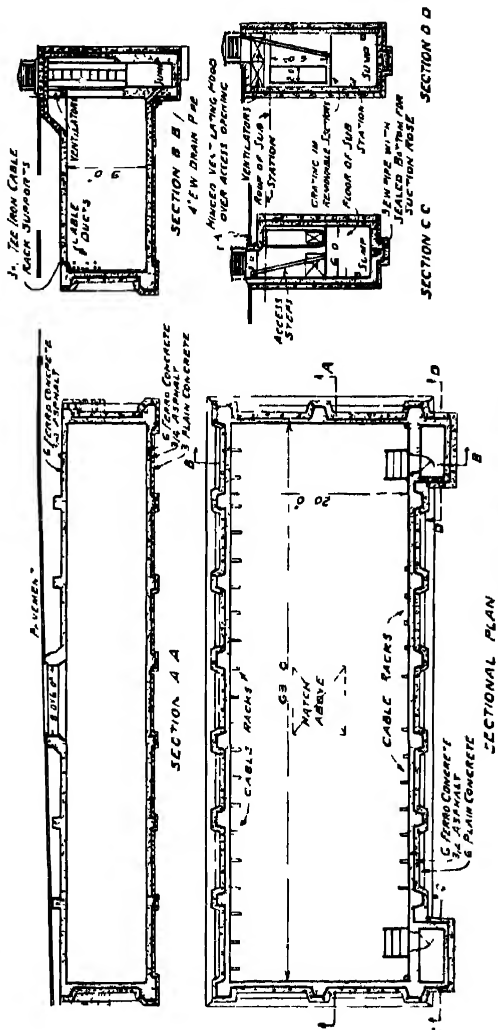


FIG. 77. Underground sub-station.

Supporting Structures. Structures should be designed to carry the transmission lines, conductors, insulators, isolating switches and other fittings under the specified conditions of loading and factors of safety. The rigidity of the structures should be such that the alignment of the equipment which they carry shall not be disturbed by the loads to which they are subjected. In calculations of the factor of safety the strength of compression members is usually based on the

crippling loads as given by an approved formula, the strength of tension members being based on the elastic limit. Structures of galvanised rolled steel members bolted together, reinforced concrete posts and wood poles are used. Standardisation of details is desirable and sizes should be kept within reasonable limits to facilitate transport, erection and inspection. Pockets likely to hold water should be eliminated or otherwise be drained. The thickness of the principal members is usually $\frac{3}{8}$ in. or not less than $\frac{5}{16}$ in. for outdoor working, and the

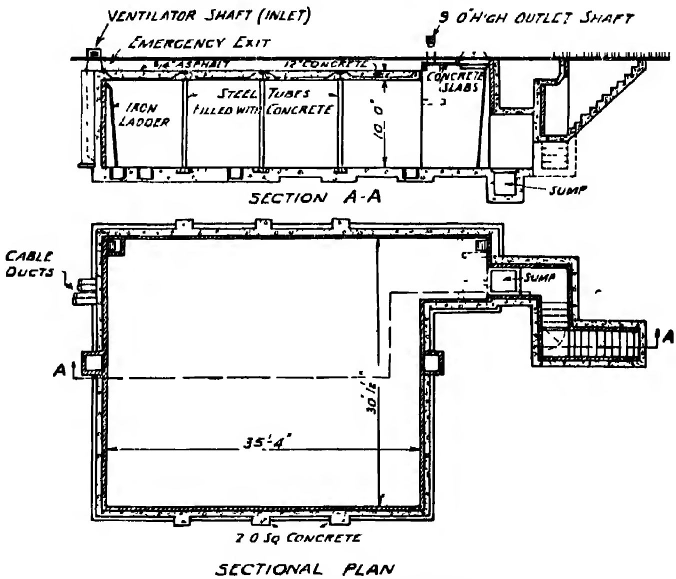


FIG. 78. Underground sub-station.

smaller bracings $\frac{3}{16}$ in. or $\frac{1}{4}$ in. Bolted surfaces should be thoroughly coated with red lead or other approved paint during erection. To facilitate inspection and maintenance steps, handrails or other facilities should be provided. If spacing is adopted as an alternative to screening, the clearances should permit visible, obvious and preferably symmetrical grouping of sections, having regard to the work to be carried out, including the handling of tools and materials. The method and point of access to high sections should be considered, and in this respect fixed ladders are useful in facilitating access with safety, and also reduce the need for handling long portable ladders. Where

direct access between sections along a structure is possible, a dividing screen is desirable since it defines a dangerous area.

Outdoor Equipment Materials. The important feature of outdoor sub-stations is their low cost compared with indoor types. In order to reduce costs, economies should be effected when specifying materials, methods of assembly and corrosion protection. The materials should be chosen having regard to the strength and nature of loading, cost, natural corrosion resistance and the type of structure or component with which the material is to be used. The size of the structure and type, nature of service conditions, possibility of prefabrication and cost of scheme will all have some influence on the methods of assembly to be adopted and the extent to which standardisation can be effected. The problem of corrosion and the form of protection to be adopted will quite frequently depend upon the materials employed and the severity of the atmospheric and other conditions generally obtaining on site. The material usually adopted for outdoor work is mild steel for structural work and in some cases aluminium. Reinforced concrete is also used because it presents little or no corrosion difficulty, although treatment of the surfaces with a silicate of soda filler can often prove useful and prevent disintegration of the concrete. Cast iron and aluminium are often used for the larger castings and for many smaller applications zinc-base die-castings are used. Methods of assembly influence material selection and finishing considerations, and, where possible, normal bolting and screwing methods are generally applied to fixings which require periodical replacement. Bolts sometimes seize in the holes but phosphate pre-treatment often overcomes this tendency. With welded assemblies, difficulty arises with corrosion protection of the welded areas, the resistance of which is generally lowered by the presence of impurities and blowholes. Constructionally, however, welding has many advantages, both from the point of view of strength and cost. External steel surfaces should be protected by painting, or hot galvanising, after all drilling, bending, machining, etc., has been completed. A priming paint containing high purity iron oxides or red, orange, blue or basic white leads in oil varnish is suitable. Assuming a satisfactory priming coat, a second coat can consist of inert pigments such as graphite, micaceous iron ore, either alone or in combination with white or blue lead, zinc lead oxide, or aluminium powder, in oil varnish. This normally gives protection for about five years. Internal surfaces of circuit breakers and transformers should be finished in an oil-resisting varnish. Surfaces in

contact with insulating oil should not be galvanised or cadnium plated, as this is liable to cause sludging of the oil. Fixing bolts may be in galvanised steel, phosphor bronze, Monel metal or Everdure. Due to its cheapness, galvanised steel is often preferred.

The nuts may be tapped oversize before galvanising or tapped out after galvanising, and well oiled before screwing up. Male threads are usually brush galvanised. Phosphor bronze bolts are often tinned. Hexagon and square-headed Lolts are suitable for lower voltage connections, but round-headed bolts are preferable for higher voltage work in order to reduce corona discharge. Some engineers have suggested that galvanised bolts should be copper-plated when used to clamp copper connections, but there are objections to this practice. While the copper forms a continuous protective coating, the zinc (in the galvanising) beneath it can serve no useful purpose, but once the copper begins to fail it will promote corrosion of the zinc and the whole coating will quickly disintegrate. This failure will be much faster than if the galvanised bolt were merely in contact with the copper connecters. Galvanised bolts should not be used for fixing copper ; if a steel bolt is required, simple copper plating would be much better and also simpler to apply.

Busbars should be of electrolytic copper, and for long spans where greater mechanical strength is required may consist of steel tubes clad with the requisite thickness of copper. Connection and busbar clamps may be in cast copper, chromium copper or gunmetal. For connections in contact with the earth, silicon copper is suitable. When connecting aluminium or steel-cored aluminium conductors to copper terminals, the joints must be protected from moisture, otherwise there will be corrosion due to electrolytic action. If this is impracticable, the joints may be made via a bi-metal strip which conforms to the conductor shape.

Isolator contacts may be fitted with shrouds to prevent the ingress of snow or alternatively have toggle action contacts designed to break any ice film which may form whilst they are in the open position.

Condensation in the spout meshings of metal-clad switchgear is difficult to deal with, especially in industrial areas where sulphur dioxide may well be present in the atmosphere. These bushings are not exposed to the cleaning action of the elements as are ordinary outdoor bushings. The condensation on the live metal results in corona discharge and the formation of nitric acid. This attacks the metal contacts and can cause severe corrosion. One way of remedying

this is to silver-plate the current carrying parts and tin other metalwork in the spouts.

Expansion joints should be included in the busbars to allow for differential expansion of the copper conductors and the steel structure, and also allow for movement of heavy gear due to settlement of foundations.

In addition to the hazards of weather, such as rain, snow, ice and wind, outdoor sub-stations may be required to be suitable for reliable and efficient operation in industrial areas where the atmosphere is polluted with corrosive gases, or in coastal areas where salt-laden fog and spray are the principal corrosive agents.

Access. Adequate access from a public road is desirable for all large sub-stations to facilitate handling of plant. Basement and yard sub-stations should also have reasonable access, otherwise difficulties will be experienced during installation and replacement of plant.

A special type of sub-station is that for receiving overhead lines ; it has a transformer chamber on the ground floor, switchgear on the first floor, and lightning arrestors, etc., on the top floor. It was popular in early coal mining areas where the primary sub-station of the supply authority served two or more collieries which were perhaps some miles apart.

It is usually difficult in built-up areas to find a site that is both near enough to the centre of the electrical loads, and yet far enough from obstructions to permit of higher voltage overhead lines to approach with any degree of safety. There is also difficulty in orienting the building to obtain a good arrangement of incoming and outgoing overhead lines both inside and outside. Further, the approach of the lines to many of the sites would necessitate the provision of expensive guarding. Generally, it is cheaper to place the sub-station on the best site available from the viewpoints of access, handling of plant and economical connection to the consumers' load, and run higher voltage cables from the sub-station to the most convenient points for the termination of the overhead lines. The inclusion of a length of underground cable at the end of an overhead line also serves as an effective surge dissipator.

Reasonable facilities should be provided for handling and installing the plant, thereby reducing the cost of erection, and enabling the sub-station to be put into commission without delay. Large and medium size transformers are usually delivered to site on a special truck, and are either jacked and lowered or lifted direct from the truck.

They are then pulled into the chamber or outdoor bay by means of block and tackle attached to a substantial hook or a short section of rolled steel joist (having a hole near the top) grouted into the concrete floor or raft. Transformers are fitted with either skids or rollers to facilitate handling. A switch-truck will usually deal with the heavier switchgear components. Provided sub-stations are so placed that reasonable road access to the buildings with heavy vehicles is possible, then no great difficulty should be experienced.

The finished surface of the site may be gravel, granite chippings, rolled tarmac, concrete or rolled ash. First cost, maintenance and excavation have to be kept in mind, for oil soakaway pipes, cables, and even weeds have to be considered. A rolled ash surface on a good heavy hard core is suitable, especially for the surrounds to many of the smaller sub-stations. An enclosure of steel palings of angular or circular section, 8 to 10 ft. high, generally proves satisfactory, although it does not entirely prevent unauthorised access. A 6 ft. high Penfold chain link fence is quite suitable for enclosures. Concrete troughs may be included to accommodate multicore cables, conduits, pipes, etc., wood supports being provided to keep them clear of the floor of the trough.

Bibliography

W. C. Bexon. " Methods and Capital Costs of Distribution over an Extensive Area," *Proceedings I.M.E.A.*, 1927.

T. H. Carr. " Some Constructional Features of Electricity Sub-stations," *Electrical Industries*, May and June, 1946.

F. Favell and E. W. Connon. " The Ventilation of Sub-stations," *Journal I.E.E.*, Vol. 90, 1943.

L. H. Fuller and C. R. Clarke. " Sub-stations with Particular Reference to Yorkshire Practice," *J.I.E.E.*, Vol. 96, Part II, No. 2, June, 1949.

P. V. Hunter. " Static Sub-station Design," *Journal I.E.E.*, January, 1911.

T. D. Oswald. " Heat Dissipation from Sub-stations," *Electrical Review*, August 25, 1944.

A. Whittaker and R. McEvaddy. " Outdoor Equipment Materials," *Mechanical World*, June, 1950.

CHAPTER IV

LAYOUT OF PLANT

THE choice of the type and capacity of plant to be installed will depend on many factors, most of which are generally peculiar to the local electrical system.

The principal items of plant which may have to be accommodated are :

(1) Higher voltage switchgear.
(2) Transformers.
(3) Converting plant.
(4) Lower voltage switchgear.
(5) Cables.
(6) Power factor improvement plant.
(7) Auxiliary equipment.

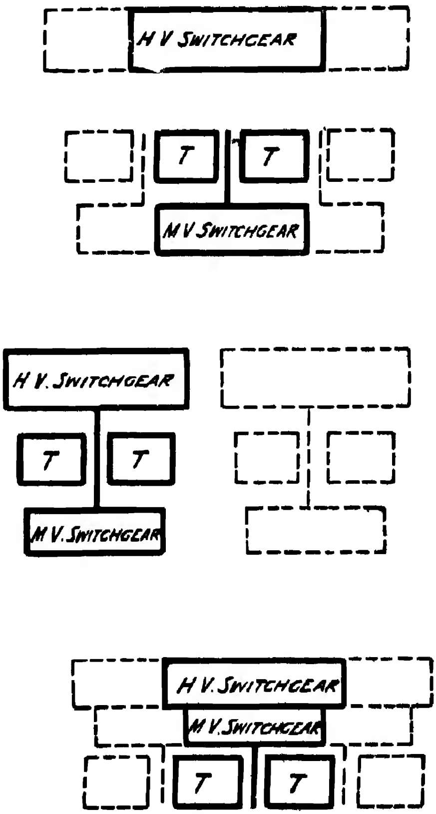


FIG. 79. Alternative layouts of transformers and switchgear.

The first step towards the ideal layout in the design of any sub-station is to adopt an ordered layout in which not only the main plant is arranged in a systematic manner, but also the interconnecting equipment and all auxiliary apparatus. Ordered sectionalisation and simplicity are really the essentials of good design. The general principles governing the arrangement of the plant in a sub-station are based on the endeavours to obtain the maximum reliability under the worst possible operating conditions. The layout and interconnection of

the plant varies somewhat with the supply authority's obligations regarding the continuity of supply, and is also governed by the behaviour under normal and abnormal operating conditions of the various sections of plant concerned. Probably the best way of considering the sub-station equipment is to refer briefly to the types of plant under review, and to illustrate layouts which have been found from experience to give satisfactory service, Figs. 79–88.

In planning sub-station equipment it is advisable in the interests of operation to commence at the power station and maintain a uniform method of notation, relative layout and colouring of phases. The same sequence should be observed in the cables throughout the switchgear, transformers and converting plant. This also applies to the lower voltage sides of the switchgear and transformers, likewise to the low voltage cables, network boxes, fuse pillars and the cutouts on consumers' premises. It is desirable that the phase rotation, polarity and angular displacement between the higher voltage and lower voltage windings of all transformers on the system should be the same. Neglect of such details in the early days of the development of systems may result in considerable inconvenience during later years when interconnection becomes inevitable. The advantages of being able to interconnect sections of a large network are obvious, and standardisation of phase relationship is therefore essential. Where consumers desire some degree of control, the higher voltage switchboard (and, if necessary, medium voltage transformer panels) may be placed in one chamber, access to this being only obtained by an authorised person of the supply authority. A separate chamber is provided for the switchgear under the consumer's control. This arrangement has the advantage that the supply authority's switchgear cannot be interfered with, and the consumer is at liberty to put in such medium voltage switchgear as he desires.

Higher Voltage Switchgear. Of the many elements which enter sub-station design, the higher voltage switchboard is probably the most important, for serious failure may cause a shut-down, not merely of the supply from that station but also of a portion of the system with which it is connected. Care must be taken in its selection, so as to ensure high reliability under all conditions of service. The functions of switchgear may be summarised as follows :

(1) To localise the effects of faults by operation of protective equipment, and so automatically disconnect faulty plant from the system.

(2) To make and break efficiently short-circuits without giving rise to dangerous conditions.

(3) To facilitate re-distribution of loads, inspection and maintenance on the system.

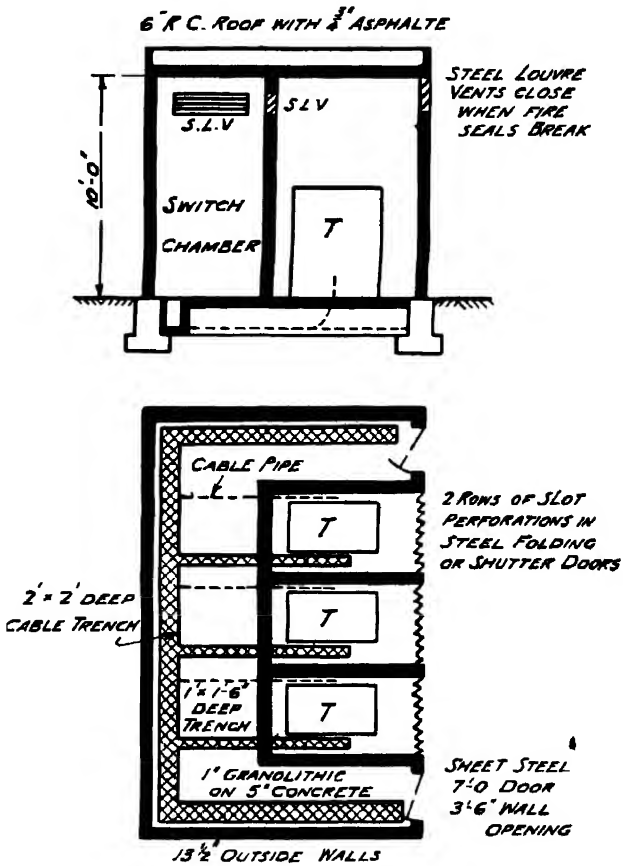


FIG. 80. Transforming station layout.

The rapid increases in demand for energy, and the necessity for taking every precaution to ensure continuity of supply, have made it essential to carry out reorganisation of many of the existing substation switchboards.

The choice of suitable switchgear is governed by the maximum short-circuit M.V.A. which it is called upon to deal with, and also in

some degree upon its relation to the system of which it forms a part. The exact value of the rupturing capacity of the switchgear is generally rather difficult to estimate, because of the complicated nature of many systems. It is necessary to obtain some idea of the magnitude, so that suitable circuit breakers can be installed, and the worst possible condition will govern their selection. The magnitude of possible fault currents depends on many factors which may vary from hour to hour on a large interconnected system. Possibly the two extreme conditions would be : a severe short-circuit at times of heavy load and lagging power factor, and a mild short-circuit during times of light load and

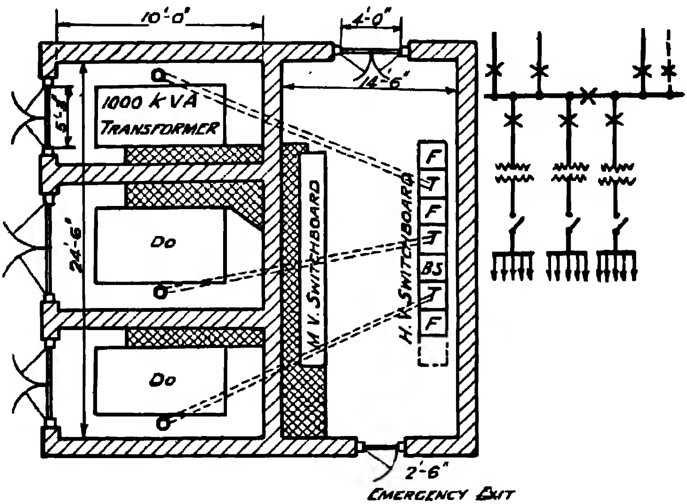


Fig. 81. Transforming station layout.

leading power factor. The former would be the worst condition, whilst the latter gives the smallest fault current, since the alternators are under-excited with a corresponding reduction in terminal voltage. Circuit breakers have been known to fail when dealing with a very small fault current—much lower than their rated capacity. Supply authorities should ascertain, record and keep up to date short-circuit values which may be attained at the various points on their transmission and distribution systems. This is especially necessary when the margin in switchgear rating depends on sectionalised distribution, or where reactors are introduced to limit the maximum values. Simplified system diagrams appear to be the most convenient form by which this information can be recorded and located. Systematic and simple

design and proper sub-division of switchgear is the surest method of obtaining reliability of supply without entailing undue expense, not only in the first installation but more so as the station grows. The oil-immersed circuit breaker has to date been most favoured for sub-station service, but air-blast breakers have been adopted in a number of installations and appear to be giving satisfactory service.

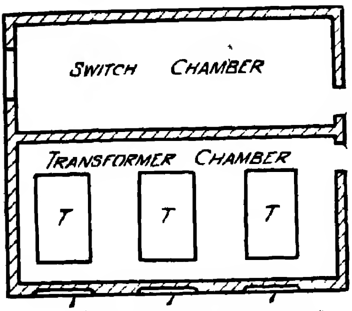
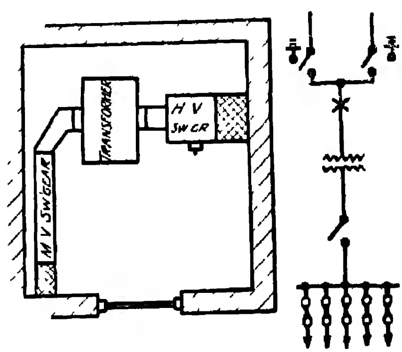


FIG. 82. Alternative layout.

When designing a sub-station, the first step is to prepare a single-line diagram of main electrical connections. This should show the busbar arrangements, circuit breakers and reactors, and may gradually be added to include all protective apparatus, instrument and voltage transformers. The next step is to decide the arrangement of the switchgear, and this will be governed by a number of factors, probably the most important of which are reliability, safety, flexibility, simplicity, space and cost. Other factors having a direct bearing on the layout are the capacity of the sub-station, method of control, number of feeders, and the system of connections adopted. The main switchgear is usually housed in a separate building or chamber placed as close as possible to the transforming and converting plant. This layout reduces the cost of land, buildings and cabling.



IG. 83. Layout of small sub-station.

The busbar arrangement is worthy of close attention in the higher voltage stations; and usually the choice lies between single and duplicate busbars. Where there is no necessity to deal with alternative

unsynchronised supplies, it is seldom necessary to provide duplicate busbars. Many engineers, however, prefer duplicate bars for the following reasons :

(1) Cleaning, repairs, modifications and extensions may be carried out without interruption of supply.

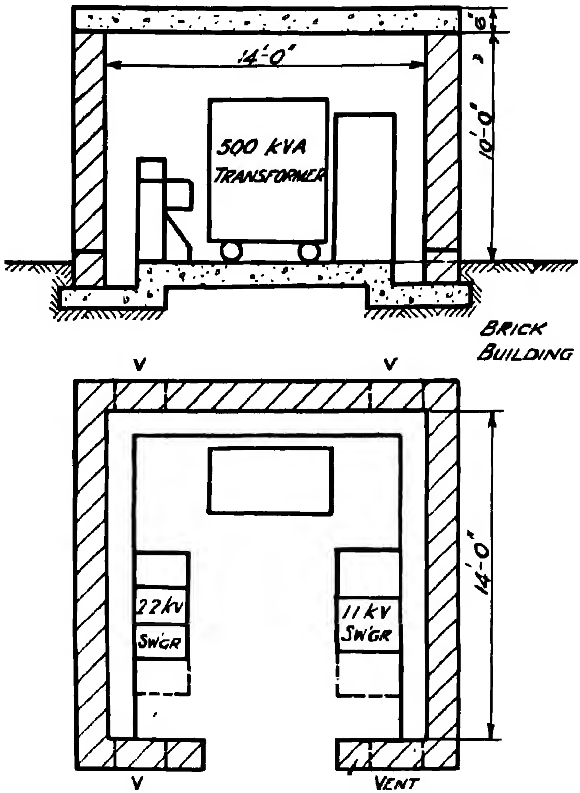


FIG. 84. Single floor sub-station.

(2) Feeders may be isolated from the system and operated at different voltages.

(3) Feeders which have undergone repair, and circuit breaker extensions, may be tested before putting into commission.

The flexibility of a double busbar is well recognised and it is first choice when an outdoor sub-station is considered. Location and

space factors, however, often dictate indoor construction, and a single busbar is frequently employed.

A bus-coupler and bus-section circuit breaker usually complete the main switching arrangements. The bus-coupler breaker is very useful in the event of failure of the closing circuits of feeder breakers, in which case these breakers may be closed manually on to the spare busbar and put into circuit by way of the bus-coupler. With the bus-coupler closed, a feeder or transformer may be changed over by closing its selector switches on both busbars and then opening the isolator on that busbar from which the circuit has to be disconnected. This cannot be done with breakers which are isolated by movement of themselves, as with certain types of metal-clad gear, the isolator selector switches must not be interlocked. A bus-section switch makes it possible for work to be carried out on the busbars themselves, one-half at a time, without interfering with the supply to or from the other half.

It is essential before deciding the physical layout of the switchgear to consider the principles which should be followed and these may be summarised as :

(1) The design of individual circuits should be such that the risks of failure are reduced to a minimum.

(2) Barriers and partitions should separate each unit so that a faulty unit will not interfere with its neighbours. Complete sub-division avoids as far as possible any serious trouble spreading and damaging the adjoining units or sections.

(3) The layout should be such that any section may be isolated without unduly affecting the service.

(4) To provide easy and safe access for maintenance and general routine inspection.

(5) Reactors necessary to keep the rupturing capacity within the specified duty of the circuit breakers.

(6) Provision should be made for handling oil and dealing with fires.

(7) Earthing conductors should be of adequate current capacity throughout—especially at joints and sections—and be suitable for carrying the maximum phase-to-phase fault current for short periods.

(8) A properly planned scheme of automatic electrical protective equipment should be installed. Such a scheme on any large sub-station may necessitate the use of overcurrent, restricted and un-

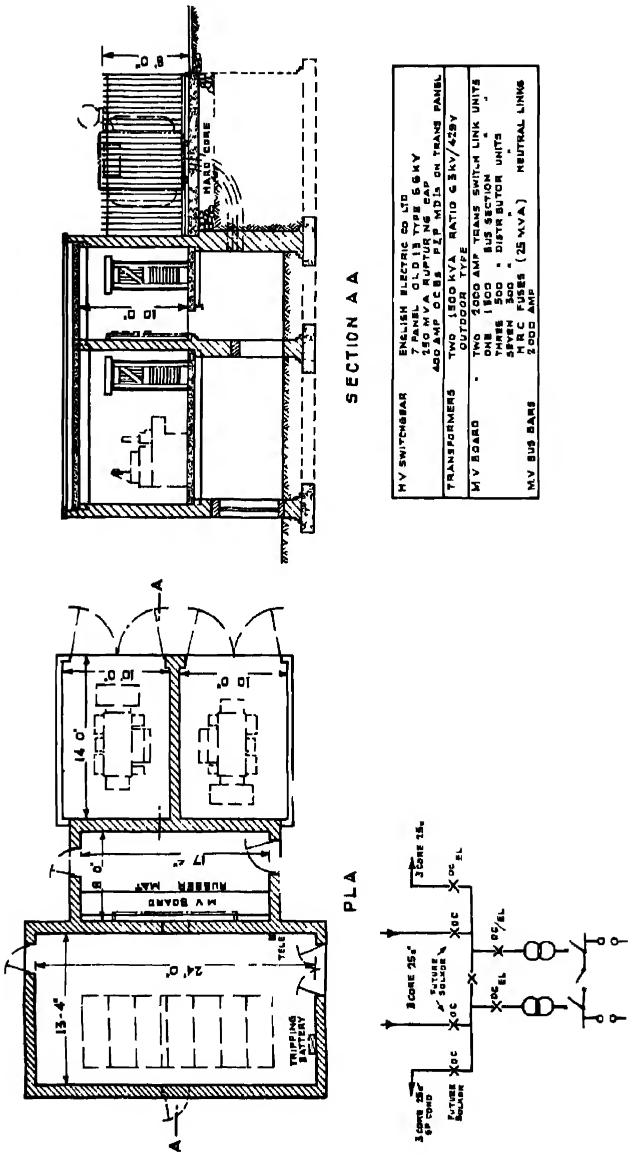


FIG. 85. General supply sub-station.

restricted earth leakage, balanced current and bus zone protective apparatus.

(9) Complete segregation of main and control cables with fireproof protection as deemed necessary.

(10) Fireproof switchrooms and cable chambers with provision for artificial ventilation, to permit of ready access and to facilitate restoration of supplies.

(11) Limiting the use of very heavy current-carrying switchgear, say, to an ultimate maximum of 2,000 amps. per circuit.

(12) Sealing all holes in switchroom floors and providing substantial supporting arrangements for all cables, having regard to fire and consequent melting of lead sheaths.

The higher voltage switchgear may be placed in a separate chamber and fitted with remote mechanical operation to ensure safety of the operator in the event of circuit breaker tank explosion when closing on to a fault. This remote control feature is employed on some recent installations, but, speaking generally, remote solenoid operation is favoured for the majority of the more important switchboards. The operating gear is sometimes arranged to project through a brick wall or an asbestos-steel barrier, and the operation of the breakers is carried out on the side of the wall away from the breakers, *i.e.*, at the back. This gives confidence to the operators and helps to ensure definite making of the circuit. An explosion may occur on a circuit breaker at the moment of closing which may damage neighbouring panels and injure the operator. It cannot be said, therefore, that the placing of the higher voltage switchboard in a separate chamber is absolutely perfect, and in larger sub-stations further precautions in the form of electrical sectionalising and physical subdivision are essential. Cellular type switchgear does afford some degree of protection in this respect, and the extra cost of buildings and switchgear entailed may be justified in certain sub-stations. Some engineers do not favour the use of a small layer of insulating material (*see* B.S. 116) since, whilst this may be satisfactory when installed, damage in service or during changes may occur and lead to a false sense of security.

The distinctive feature of kiosk construction is external operation, and mechanical means of operating isolators is desirable so that cell fronts need not be opened, especially in the dark. In rural areas the kiosk steel sub-station and outdoor layouts are generally finding favour. Metal-clad switchgear has the advantage of allowing easy access where space is restricted. A station designed to deal with the average rural

load is equipped with open type gear and embodying improvements from both operating and safety points of view. For pole type sub-station service, sheet steel cubicles are strong but suffer from "sweating"

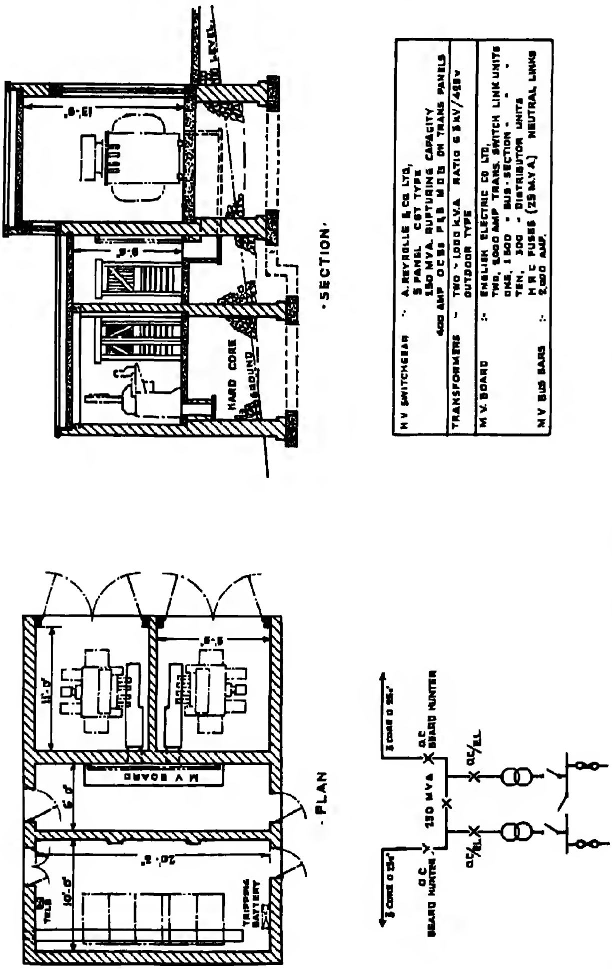
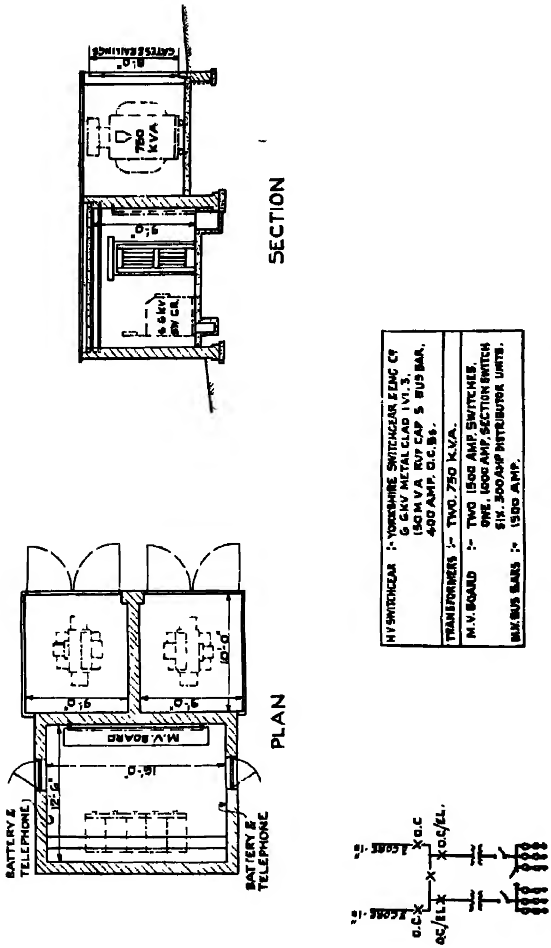


FIG. 86. Gen upp b-station.

and are expensive compared with wood cubicles. The latter make quite a sound job when adequately braced, creosoted and provided with substantial fittings.

The medium voltage switchboard and fusegear are not quite open

to the same objection, for they are not so liable to explosion owing to the limited short-circuit power that can pass through the transformers.



H V SWITCHGEAR	:-	YORKSHIRE SWITCHGEAR & ENG Cº 6.6KV METAL CLAD IVI.3. 150 M V A RUP CAP S BUS BAR. 400 AMP. O.C.Bs.
TRANSFORMERS	:-	TWO. 750 K.V.A.
M.V. BOARD	:-	TWO 1500 AMP. SWITCHES. ONE. 1000 AMP. SECTION SWITCH SIX. 300 AMP DISTRIBUTOR UNITS.
M.V. BUS BARS	:-	1500 AMP.

FIG. 87. General supply sub-station.

The usual assembly of switch and fusegear is therefore reasonably sound and makes quite a simple layout.

Under higher voltage switchgear it is appropriate to include that provided on rural distribution networks. Instead of earthing the neutral 6·6 kV three-phase branch lines for rural systems, the practice

of earthing one of the phase lines has been adopted with satisfactory results. This has the advantage of permitting the use of double-pole fusing and switching on normal three-phase systems and single-pole on the more frequent single-phase branches or spur lines. Further, the disadvantages of unattended higher-voltage fused tappings are reduced by the introduction of reliable auto-reclosing switch-fuses.

Transformers. There are three principal classes :

(1) Single-phase ; (2) Two-phase ; (3) Three-phase.

The first-mentioned is smaller, lighter and easier to handle and

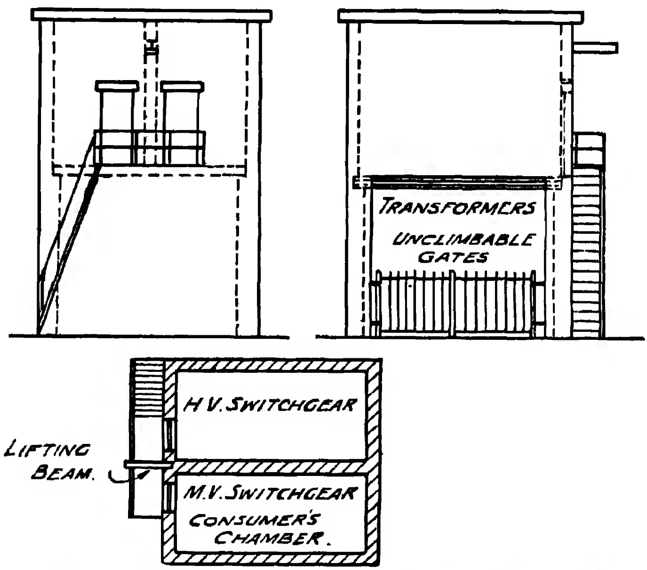


FIG. 88. Layout of sub-station to make use of small ground area.

transport than three-phase units, and only one other single unit need be provided as a spare. On the other hand, three-phase units require less space, are cheaper, and for a given output are not so heavy ; further, the cabling and connections are simpler and less costly.

Two-phase units are generally of the Scott type and have proved especially useful for domestic distribution services. Single-phase units are usual for domestic and lighting services.

The layout of transformers is along standard lines, and they may be placed either indoors or out-of-doors. Transformers in commercial or city buildings create a fire risk, but special non-inflammable

insulating materials are now available and modern fire-fighting equipment is very effective and reliable. Outdoor transformers require more maintenance, especially painting in industrial areas. On the other hand, there is a saving in building costs. Consideration should be given to the arrangements for access, handling, unloading, inspection and maintenance. The general practice for smaller network sub-stations is to install one transformer, and if adequate spares are to hand and adequate facilities are provided for rapid replacement, this

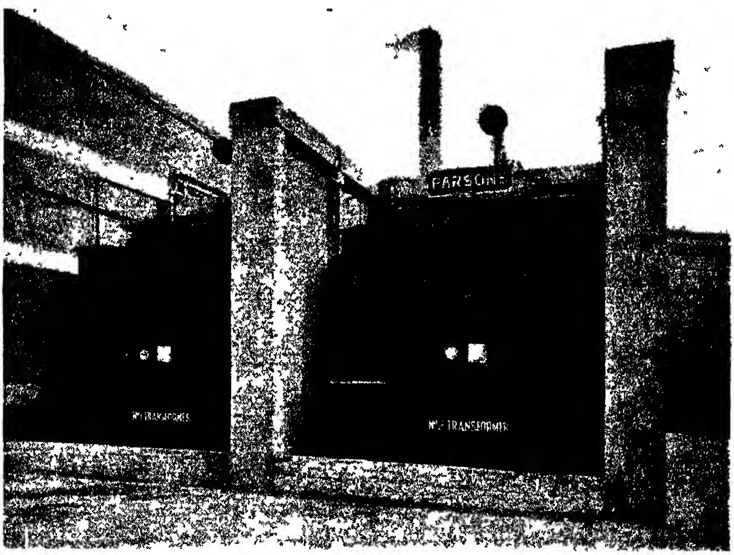


FIG. 89. 2-10,000 kVA 33/6·6 kV three-phase transformers in primary sub-station.

appears to be reasonably sound, for transformer breakdown is rare. If network connections do not allow for maintenance, then in the more important sub-stations two transformers are preferable. The question is really an economic one, and if the installation period coincides with good purchasing, and growth of load is anticipated, the latter scheme will no doubt be justified.

The transformers should be arranged (Figs. 89 and 90) so that a faulty unit does not endanger its neighbours in the event of explosion or ignition of oil. Where transformers are of the indoor type they are housed in brick or concrete cubicles separated from other plant. The effects of an explosion followed by a fire on one transformer have a

reasonable chance of being isolated from the remainder of the plant. Separate chambers make inspection, maintenance and repair work on the transformers safe. A man may, however, enter a live transformer chamber in error for a dead one, unless some interlocking arrangement such as the key type is fitted to ensure that both the H.V. and M.V. switches are open before he can touch live metal in the chamber. If space permits and the units are not more than 500 kVA capacity it is reasonable to place one unit in the switch-chamber to warm the building.

To restrict the flow of oil in case of tank failure, a brick surround

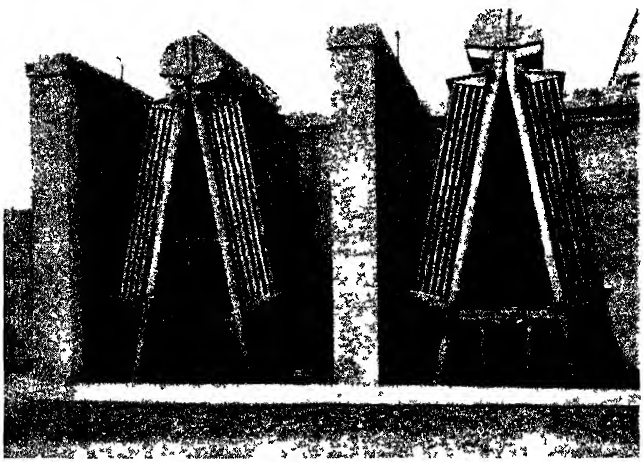


FIG. 90. Cooling radiators beyond the division wall in similar compartments to Fig. 89. Water fire-fighting equipment

18 in. high, filled to a depth of 6 in. with pebbles, appears to be quite suitable for transformers up to 500 kVA. The need for some degree of fire protection has been widely discussed in recent years, although it is a matter of experience that transformers give but little trouble. Nevertheless, the spreading of burning oil from a damaged transformer calls for consideration. Transformers of reasonable output are fitted with explosion diaphragms which afford protection against tank failure. Outdoor units may be spaced, and an additional precaution is the building of walls between and around the units. These walls should be at least 9 in. thick and built to extend just above the

transformer bushings or top of the cooling tubes, thus affording protection in the event of an explosion and consequent fire on adjacent units. Dwarf walls may be provided for end transformers, also for the front of centre transformers.

As is the case in all designs which have the transformers placed between the higher and lower voltage switchgear, difficulty is experienced in arranging for unlimited extensions and at the same time providing access for transformers.

Weep holes should be included in the walls to allow rainwater to leak away. Where large transformers are installed it is desirable to include ample drainage to soakaway pits around the units. The pits should be of such size that any leakage of oil up to complete rupture of the tank is led away and quenched. Some straining medium, such as granite chips or pebbles, will suffice in the ducts or pits. The surfaces of surrounding soakaway areas should not be allowed to become clogged due to the accumulation of dust, etc. Where transformers are in the vicinity of residential property, care should be taken to minimise the emission of noise, and the principal design factors in reducing the noise level are a reduction of the flux density and a substantial and well-clamped core. A further precaution is the inclusion of anti-vibration pads between the transformer and its foundations. Rubber of suitable proportions and loading has proved satisfactory. Layers of cork and lead damp out noise due to transmitted vibration and foundations may be sectionalised by the inclusion of bitumen filling. Other methods of preventing emission of noise are : to house each unit in a massive brick or concrete chamber the entrance of which is finally closed up, or to surround the transformer tank with sound absorbing material.

Transformer noise may be caused by an incipient cable fault. In one city sub-station where sound proofing was important the transformer chambers, walls and ceilings are lined with material about 4 in. thick. The transformer foundations are built as structures independent of the building to prevent vibration from being picked up and transmitted to the outside. There are no windows in the building, thereby eliminating another noise escape path.

Underground transformer pits, particularly for units up to 300 kVA, require attention in regard to ventilation, drainage and access. A simple and satisfactory arrangement is to place the fuse pillar in a nearby wall and the transformer in a pit under the footpath immediately in front of the pillar, and connect by ducts. In this way the pit

is ventilated and the pillar maintained dry. An iron tank or brick pit serves very well for such purposes. A single-phase 60 kVA transformer in which a single-pole oil-immersed switch-fuse, and 300-amp. disconnecting and tapping switch, are provided can be housed in a brick pit, 4ft. 6in. square by 6 ft. deep. A cast iron concrete filled cover 3 ft. square is fitted, which can be removed by two men.

If it is necessary to enter a kiosk transformer compartment, the higher voltage terminals and leads should be protected. The back of the medium-voltage switchboard, if the live conductors are exposed, should be screened when placed in the transformer compartment if danger exists.

With pole-mounted units arrangements have to be made to change a transformer, and if it is mounted on the same structure as the switch fusegear the lifting equipment should have adequate electrical clearance from all live parts on the incoming side of the switchgear. There does not appear to be any prescribed minimum distance of live terminals from ground level, but figures of from 15 to 18 ft. have been used with no adverse effects. The Overhead Line Regulations (Electricity Commissioners, 53, paragraph 13) give the following :

"The height from the ground of any live conductor (other than a service line), earth wire, or auxiliary conductor at any point of the span, at a temperature of 122° F. shall not be less than 19 ft. across a public road, or 17 ft. in other positions. A height of 15 ft. may be adopted in situations inaccessible to vehicular traffic."

British Standard Specification No. 162 gives recommended clearances for both indoor and outdoor working at varying voltages. The mounting of the transformer is usually by hanging on channels or bolting to a channel platform. The latter is preferable for larger transformers as it provides better access for inspection, maintenance and replacement, apart from being a stronger form of construction. A three-pole terminal structure affords an improved arrangement. The medium-voltage distributors, if there is only one circuit, can be accommodated on one or both legs of the "H" pole, but if there are several circuits, alternative arrangements are possible. The third-pole structure is one way out of this, for the third pole enables all the distributors to be pulled off it.

Converting Plant. The conversion of electrical energy from A.C. to D.C. requires one of the following four classes of plant :

(1) Motor generator ; (2) Rotary convertor ; (3) Motor convertor ; (4) Mercury arc rectifier.

Of these the last-named has grown rapidly in favour for almost all capacities met in sub-station practice.

The motor generator, although popular in early sub-stations, is now rarely adopted. Rotary sub-stations of all types are more elaborate than static stations and are of the indoor type. With rotary convertors and rectifiers, it is necessary to provide transformers in view of the voltage limitations. The motor convertor consists of two direct-coupled machines, this occupying rather more floor space, but

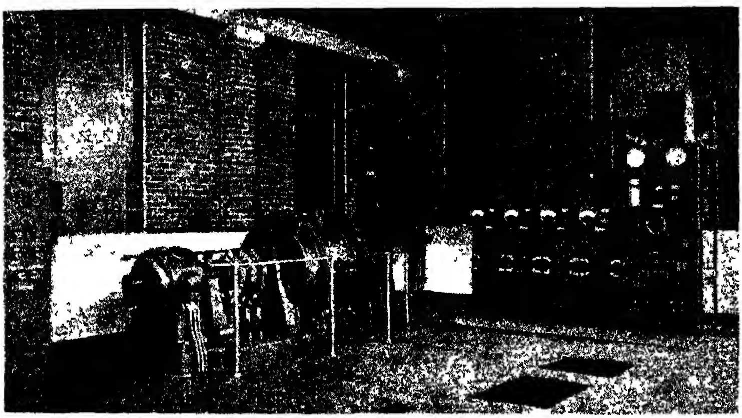


FIG. 91. 500 kW–500 V rotary convertor for trolley-bus supplies.

the absence of transformers offsets this disadvantage. Motor convertors are wound for direct connection to the higher voltage A.C. supply by way of the stator.

Rectifier transformers are larger than those associated with rotary convertors of the same output.

Convertors should be arranged so that their axes are at right angles to the longitudinal axis of the room. In this way the higher voltage A.C. switchgear and the D.C. switchboards may be placed on appropriate sides of the convertors. The commutator ends of the convertors then face the D.C. switchboards on one side and the slip-ring ends face the higher voltage switchgear on the other. The transformers may be placed out-of-doors or housed in separate compartments and thus minimise the fire risk. Many of the existing rotary sub-stations

have the transformers in the main room to take advantage of the crane for handling. In some cases the transformers have been placed in pits in the machine floor. The advantages of this arrangement are that it

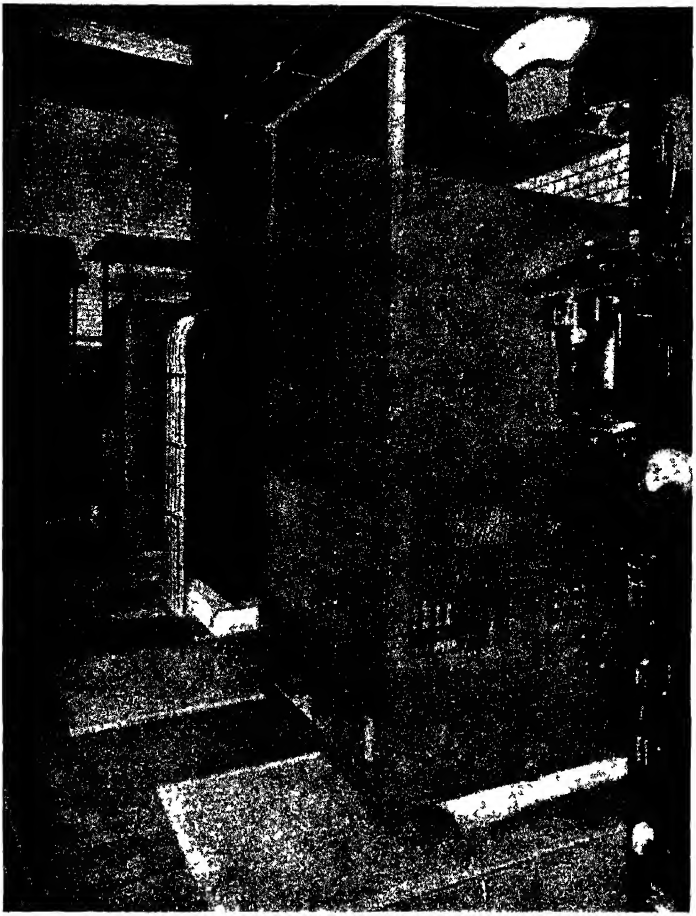


FIG. 92. 2–500 kW glass bulb rectifiers for trolley-bus supplies (Hewittic Elec. Co.)

reduces the building height if core lifting is required, oil spreading is restricted, and cable runs and connections are simplified.

Steel tank rectifiers may be spaced, and metal screens provided to guard all live parts and so prevent unauthorised access. With the glass bulb type, each rectifier unit is made up of a convenient number

of bulbs each of which is accommodated in a separate chamber or sheet steel cubicle. The layout should be such that any bulb may be safely disconnected and removed from all live circuits without interfering with the operation of the neighbouring bulbs. The cubicles form complete equipments and should be arranged to provide adequate access for inspection and maintenance. Cable trenches and pipes may be incorporated in the floor to suit almost any layout, thereby keeping the building free from external cabling.

The higher voltage A.C. switchgear can be arranged to meet the requirements mentioned earlier in this chapter. The D.C. control panel should be placed relative to the unit it serves, and it is possible

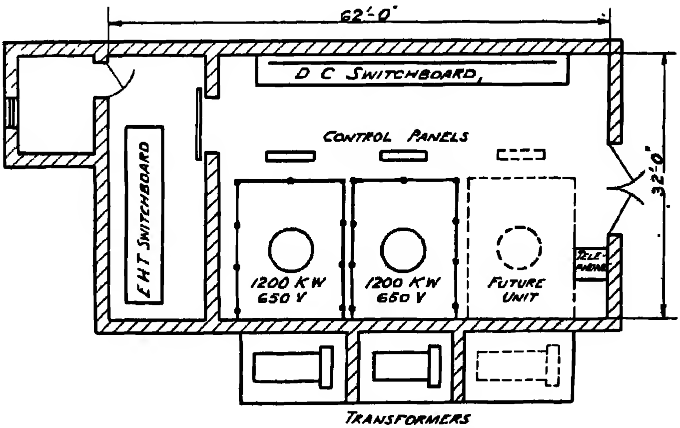


FIG. 93. Layout of steel tank rectifiers.

to have a continuous board comprising the whole of the D.C. panels. The most important piece of apparatus is the air insulated electrically operated high-speed circuit breaker, in which are included special operating features for re-closing, etc. These high-speed breakers can be mounted in separate concrete cells.

Rectifiers, especially the glass bulb type, do not need heavy foundations, and less floor space is required. The floor space is progressively less the higher the D.C. voltage required. Apart from a number of smaller auxiliaries, there are no running parts, with consequent reduction in noise. Noiseless operation is a desirable feature for substations situated in residential districts. The layout can be simplified by arranging the transformer, inter-phase reactor, bake-out windings and surge arrestors, as a unit.

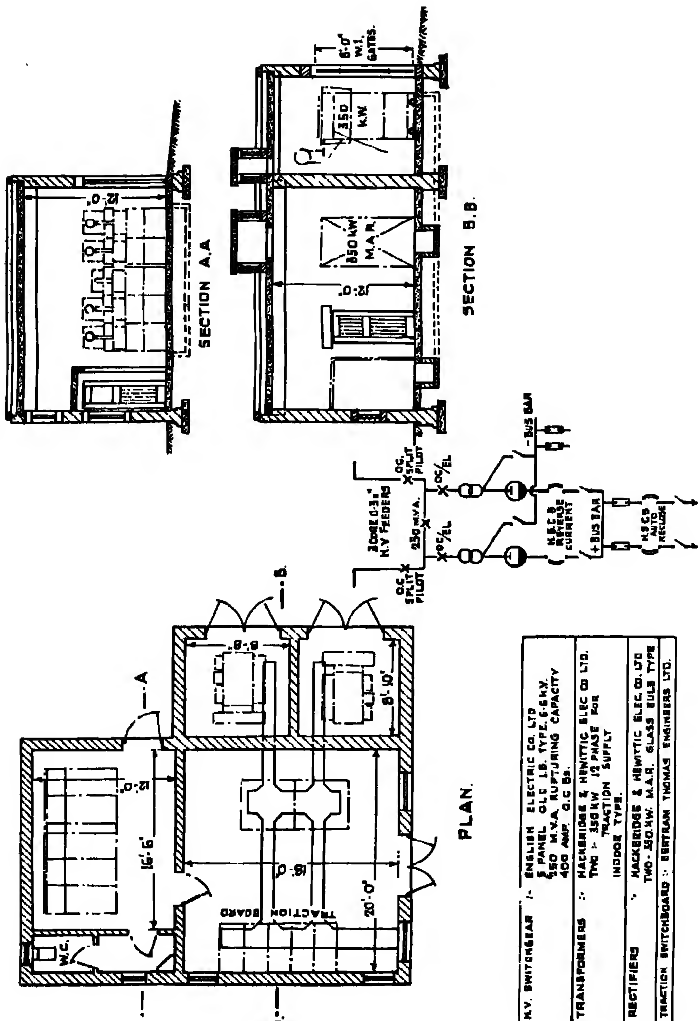


FIG. 94. Trolley-bus supply sub-station.

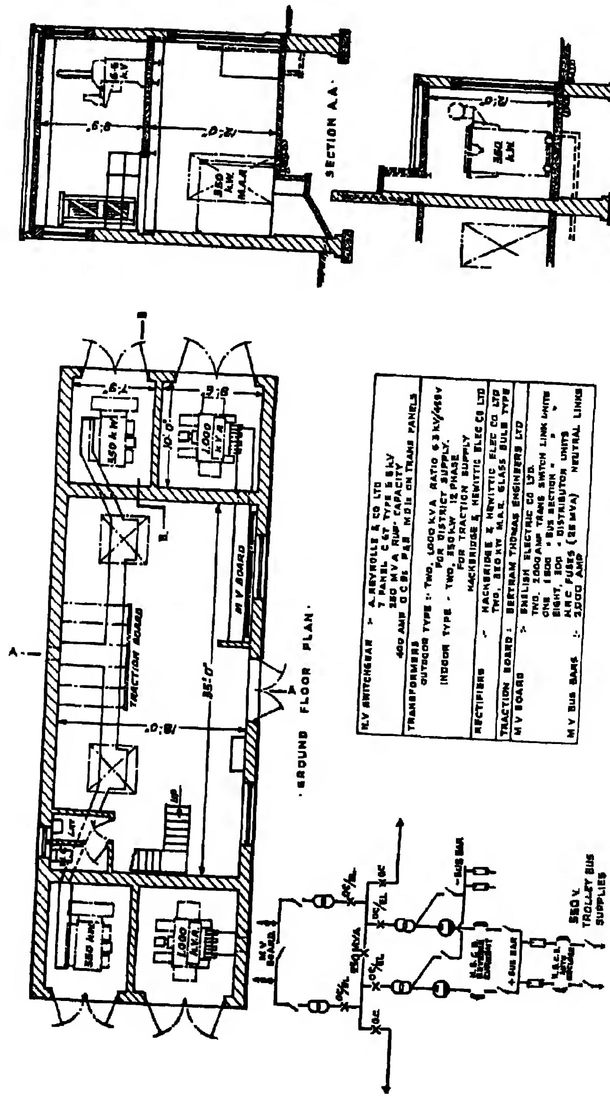


FIG. 95. Combined trolley-bus and general supply sub-station.

The rectifier and its components (the live parts of re-coolers and the water piping, etc., are carried on insulated supports), being enclosed by a metal screen, tend towards safety when general cleaning is carried out in the buildings. Two-storey buildings are not very convenient for steel tank equipments, but where site area is limited it may be necessary to resort to a basement. In larger sub-stations this may prove to be an advantage, for the rectifier units can be partly below floor level which facilitates inspection and maintenance. Lifting facilities are necessary, and a crane or lifting block is provided. Rectifiers, if fitted with wheels, can be rolled to the lifting position, but very large units are not so easily handled. Rectifiers of both the glass bulb and steel tank types lend themselves admirably to automatic control. In traction work, where a rectifier sub-station has to operate in parallel with other converting sub-stations, the rectifier is connected to the D.C. busbars through a high-speed circuit breaker arranged for reverse tripping, to disconnect the equipment from the system in the event of a back-fire. The addition of bulbs as required makes a very flexible arrangement, and allows for growth of load at reasonable initial expense. The glass bulb rectifier is very good where D.C. is required at reasonable loads and medium voltages. For very heavy currents at rather low voltage—as in electrolytic work—the rotary and motor convertors usually prove the best from an efficiency point of view. Figs. 91–95 show typical layouts.

Medium and Low Voltage Switchgear. Little trouble is experienced with this equipment, and the features outlined under Higher Voltage Switchgear apply equally well here.

Care should be taken to maintain the regulation clearances, etc., when open type and fuse distribution boards are installed. If the prescribed dimensions cannot be obtained, the conductors must be suitably screened. A similar result in so far as the rear passageway is concerned may be achieved by placing the switchboard as close to the wall as possible, so that access to the back is impossible. Danger lies in allowing a space which is just sufficient to admit a person, or even the entry of an arm. Fuse-type gear is the general practice, although three-pole circuit breakers on the outgoing medium-voltage distributors are used to avoid the troubles which may arise due to the blowing of a fuse on one phase. Further, it is easier to close and trip a circuit breaker on load than to manipulate fusegear. The amount and type of switchgear necessary for a distribution sub-station is found to vary considerably in practice and much depends on the opinions of

the engineers responsible for the designs. Transformers are very reliable that simple protection gear is quite suitable for many installations. The air circuit breaker, which occupies less space and involves less maintenance than an oil circuit breaker, can be used on the medium-voltage side of the transformer with overcurrent and reverse-current tripping facilities, Fig. 96. In rural districts it is preferable for a fuse

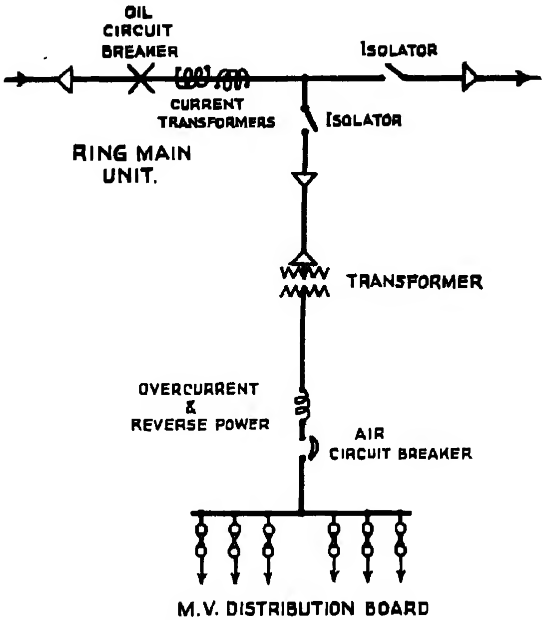


FIG. 96. Line diagram of distribution sub-station.

to blow on a faulty phase rather than that the entire line should go down and interrupt all supplies.

Cables and Connections. It is desirable that the cables be sectionalised to minimise damage in the event of fire. In order to limit the degree of interference in such happenings, complete sub-division of the higher and lower voltage cables is recommended. The exact positions of the cable trenches, ducts and pipes are important and should be decided upon as early as possible in the construction period. Much time is saved and a simple and neat scheme is usually obtained. All pipes and ducts should be provided with tightly fitting wood bushes to prevent the ingress of vermin. To reduce the possibility of complete

failure of a sub-station due to cable damage, it is advisable to arrange some of the cables, both higher and lower voltage, to leave the building in opposite directions. In this way, especially in the event of enemy air attack, the chances of saving at least some of the feeders and distributors are increased.

Paper insulation with plain lead covering and tape, together with steel wire armouring and weather-proofing if necessary, is usual for higher voltage service. The lower voltage cables may be of paper, cambric or rubber insulation, and, in most cases, lead covered with or

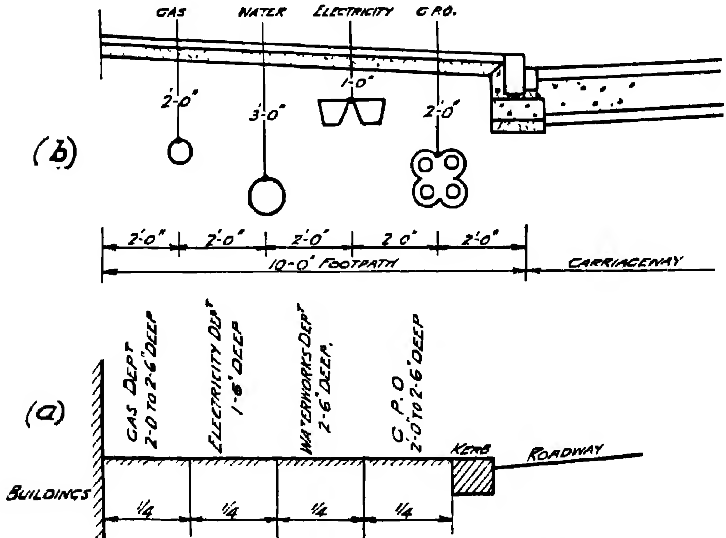


FIG. 97. Relative positions for laying services.

without protective armouring. When the route of a waterproofed cable is partly underground and partly inside a building, the waterproofing should be stripped from that portion which is exposed in the building. Where cables must of necessity pass through pipes or ducts laid beneath a sub-station floor, or are in positions in which water may accumulate, it is advisable to use lead covered cables. In one case a high voltage feeder cable supported on concrete posts alongside a railway for some four miles was found cracked in over one hundred places and was replaced and laid underground. The cracking of the sheath was apparently due to vibration.

Kiosks are often supplied from ring mains, and to realise the advantages of duplicate supplies the cable terminations should be independently accessible, preferably by enclosure in separate cells or chambers. If separation is not provided, both supply cables must be made dead before work, such as fault localisation tests, can be started. On pole-type units single core V.I.R. cables run in cleats are not altogether satisfactory, whilst paper-insulated cables suffer from the disadvantage of requiring sealing boxes. The use of rubber-insulated single-core cable—the four cores being laid up, taped, braided and compounded overall and cleated to the inside of the pole leg—make a reasonably sound job. Sealing boxes are not required, the cores being separated and the end taped to prevent ingress of moisture.

In city areas the cable positions in footpaths are usually fixed in

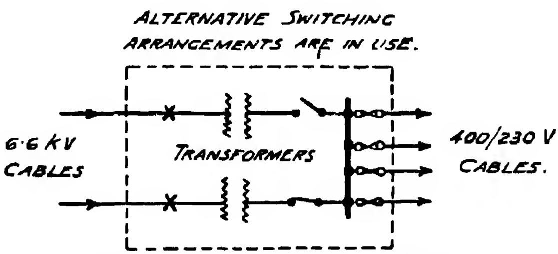


FIG. 98. Typical sub-station connections.

relation to other services, Fig. 97, and this must be allowed for. The cabling, both main and auxiliary, is part of a sub-station, and it is important that careful attention be paid to the installation. On entering footpaths, etc., the cables should be at least one foot from any gas and water pipes and post-office cables. Should it be impossible to obtain this clearance, protection should be afforded by separating the supply cable from the neighbouring cables or pipes by either 2 in. of concrete or 2-in. stone flags. Whatever form of protection is provided care should be taken to remove sharp edges which may damage the lead sheathing. Wooden spades may be provided for covering the cables with the first layer of soil and also for opening out when the protecting wood boards or tiles have been reached.

Table 11 and Fig. 98 give cable data relating to various general supply sub-stations.

Cables may be laid direct in the ground, drawn into steel, fibre or

earthenware ducts or supported on racks, hangers or cleats. Single-core cables are usually grouped in close trefoil formation to limit circulating current losses in the sheaths. Bindings of tarred yarn are applied at intervals of 2 to 3 yds. to hold the cables in position during back-filling. The duct system is useful where additional cables are required to be installed in the near future. The ducts are usually of such a size as to allow of about 1 in. clearance between the cable and the bore of the duct. Cleats for single-core cables are of non-magnetic material such as brass or wood and the latter can be treated with fire-resisting paint. Cleats for long vertical runs are designed to support the weight of the cable. A simple rule for estimating the length of a cleat is :

$$L = \frac{W}{10D} \text{ in., based on a gripping pressure of 5 lb./sq. in. of projected area.}$$

where W = weight of cable per cleat, lb.

D = diameter over armouring, in.

Special attention should be given to the cleating of cable connections to pole-supported terminal boxes, and the cable should be clamped at a distance of about 1 ft. from the lead wipe to relieve the wipe of localised mechanical stresses.

Three-core terminal boxes are usually mounted on an earthed support. For sealing ends, the possibility of circulating currents in the cable sheaths arises. Feeders consisting of three single-core cables should have the sheaths bonded and earthed at the point near each end of a run where they separate and they should be insulated at the terminations. Earthing at the terminations will result in increased sheath circulating currents on account of the wide separation. Insulation of the sheaths at terminations is provided for by using insulating glands or by mounting the sealing ends on wood blocks.

With single-core lead-covered cables for A.C. working, the current induces potentials in the sheaths which vary according to the magnitude of the current, the spacing of the conductors and the length of cable. If sheaths are bonded together and/or earthed at one point only, no circulating currents flow in the sheaths, but the potential difference between the sheaths and earth builds up proportionately to the length of cable from the bonding point. Dangerous voltages may be set up under fault current conditions. If the sheaths are bonded and/or earthed at more than one point the potentials are limited, but circulating currents flow in the sheaths (*see* Chapter VIII). The arrange-

ment of main single-core cables at the end of a route, where they split up to connect transformers, should receive careful attention. Where a number of cables per phase are used, care should be taken to maintain as far as possible geometric formation, and to avoid the presence of

TABLE 11. *Sub-station Plant and Cable Data*

Station	Plant		6·6 kV cables sq. in. phase	400/230-volt cables sq. in. phase		Remarks (Also see Fig. 98)
	Installed kVA	Possible ultimate kVA		Present	Ultimate	
A3	1,500 (2–750)	2,000 (2–1,000)	0·5 (2–0·25)	1·5	1·5	One transformer normally in service. 4-core M.V. cables (0·25).
B3	200	500	0·1	0·5	1·0	Supplies one consumer and assists network.
C3	500	1,000	0·5 (2–0·25)	0·75	1·5	Supplies one consumer only.
D3	3,000 (2–1,500)	3,000 (2–1,500)	0·5 (2–0·25)	3·75	3·75	One transformer normally in service.
E3	500 (2–250)	500 (2–250)	0·1 (2–0·05)	0·4	0·4	,,
F3	800 (2–400)	1,000 (2–500)	0·2 (2–0·05) (1–0·10)	1·0	1·0	,,
G3	2,000 (2–1,000)	3,000 (2–1,500)	0·5 (2–0·25)	3·5	3·5	,,
H3	900 (1–500) (1–400)	2,000 (2–1,000)	0·5 (2–0·25)	0·25	1·5	,,
I3	1,500 (2–750)	3,000 (2–1,500)	0·5 (2–0·25)	1·5	2·5	,,

steelwork in the direct field between phases, thereby preventing eddy and hysteresis losses in the steelwork. Non-magnetic sections may be necessary to break the magnetic circuits. Precautions against eddy currents should be taken wherever single-core cables are run through magnetic material, such as cable boxes, etc. If the magnetic material is too near the cable eddy currents are set up causing the material to heat up, which may ultimately result in breakdown. Tests figures

given will show that the hole in magnetic material depends directly upon the current carried by the cable :

Cable current amps.	Minimum dia. of hole in.
100	1
200	2
300	3
400	4
500	5

It will be observed that the diameter of the hole required for heavy currents becomes too large for practical purposes and to overcome this one half of the box or other fitting should be made of non-magnetic material. Cables should not be placed near iron nor be supported on iron cleats. With oil-filled cables, it is necessary to avoid earthing the lead sheaths through the conservator connections.

At present there is no fixed figure for maximum current density in cables, but a figure of 80,000 amps. per sq. in. for one-half second, or 55,000 amps. per sq. in. for one second, may be assumed for paper-insulated cables. Under short-circuit conditions damage to insulation by overheating or by mechanical forces should be eliminated. The current densities mentioned assume that the full value of short-circuit cur rent flows for the time specified, whereas in practice this current will fall to a much lower figure at the end of half a second than that corresponding to the symmetrical current in the first few cycles. It is often considered justifiable to work at a higher current density, and figures of 120,000 to 150,000 amps. per sq. in. have been adopted. The time period will depend on the protective gear setting which varies according to the plant and equipment protected.

One formula for estimating the sizes of cables is :

$$\frac{I}{A} = \sqrt{\frac{K.\ \delta\ 4\cdot 2}{t.p.a}\log_e\left(1 + \frac{a.\theta}{1 + a(\theta_o - 20)}\right)}$$

Where K = specific heat of copper, 0·092 gram/cals. per ° C.

δ = density of copper, 8·892 grams per cm.^{3}

t = duration of short circuit in seconds.

p = specific resistivity of copper = $1\cdot724.10^{-6}$ ohms. cm. at 20° C.

α = temperature coefficient of copper resistance, 0·00393 per ° C. from 20° C.

θ = temperature rise θ_o at t seconds.

θ_o = conductor temperature at commencement of short circuit.

Assuming the initial temperature of conductor is 70° C. (normal maximum working for 6·6 kV cables) and a final temperature at the end of short circuit 120° C., formula becomes :

$$\frac{\mathrm{I}}{\mathrm{A}} = \frac{57{,}000}{\sqrt{t}} \text{ amps. per in.}^2$$

Recommended sizes of 6·6 kV 3-core cable for varying fault M.V.A. are as follows :

0·1	in.^{2}	100	M.V.A.
0·15	,,	150	,,
0·25	,,	250	,,
0·30	,,	350	,,
0·50	,,	500	,,

Symmetrical short circuit and fault duration of 0·3 second.

The current ratings of cables, together with particulars of grouping and routes, are set out in the I.E.E. Regulations, and Cable Makers' Association publications, to which reference should be made.

Where possible on trunk routes a pilot cable should be considered with the main cable for protection and communication purposes, even if immediate use cannot be visualised.

The simplification and standardisation of connections inside a sub-station requires some thought. Bare connections to transformers in sub-stations and kiosks are not always favoured and proof of economy should be established before such a practice is adopted for permanent structures. Cambric-insulated cablework is sometimes preferred, although it has been contended that such insulation may give rise to radio interference especially on dual purpose H.V. and M.V. overhead lines. Cambric-insulated and paper-insulated cables can both be simply sealed by the application of oil-resisting tape technique, but the former has a much lower impulse strength. Cambric type of insulation should behave better than an exposed paper-insulated cable when subjected to normal atmospheric conditions as found in a sub-station. All secondary wiring should be of stranded conductor, and sweated lugs should be used. In all cases bolted connections are by steel

bolts using brass nuts and locknuts without projecting thread, to ensure that the nuts do not rust solid. Bolts of less than ½ in. diameter for main conductors and No. O.B.A. for secondary connections are not recommended.

Power Factor Improvement Plant. To enable power factor improvement to be effected it may be necessary to install condensers in consumers' sub-stations, and Fig. 99 shows a typical connection diagram.

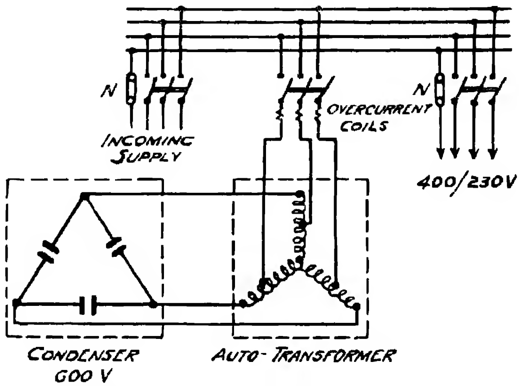


FIG. 99. Static condenser installation.

Auxiliary Equipment. The auxiliary apparatus required will depend on the type of sub-station, although the majority of the apparatus will be required in all cases. The chief items are : Overhead crane ; air compressor ; batteries and charging apparatus ; telephones ; supervisory control apparatus ; fire-fighting equipment ; lighting ; heating and tool cases.

An overhead crane and air compressor are provided in rotary sub-stations, to facilitate installation, maintenance and cleaning. Periodic inspection of cranes and high-pressure vessels is required under the Factory and Workshop Acts, and sufficient space should be provided to permit of this being done.

The batteries are for circuit breaker closing and tripping, and provide an independent supply for automatic relay tripping. Closing batteries are only used on the larger circuit breakers, except where remote control is necessary. A tripping battery encased in a stout wooden box can be wall mounted on brackets.

A telephone system is an important adjunct of modern distribution

networks, and although the additional cost may appear to be unjustifiable in the early stages, the rapid growth of electrical systems and the saving in time justify its inclusion. The telephones should preferably be connected to a private system which has its headquarters at the distribution control centre. The provision of a good private telephone system is an added asset to a large distribution network, for it facilitates operation and maintenance, and is especially useful in times of emergency. The additional cost of telephone cables is comparatively small, as they are laid during the laying of the main cables, and only point to point communication is necessary. All but the very small sub-

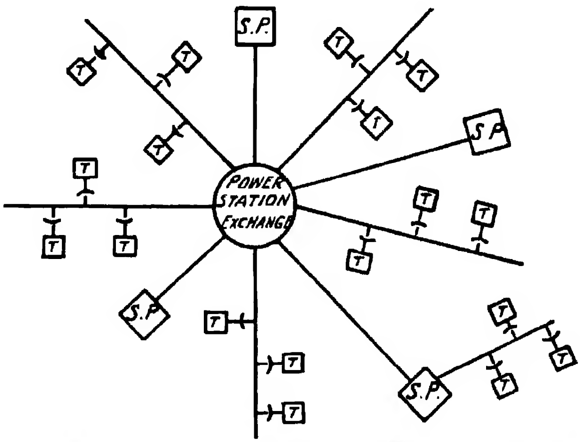


FIG. 100. Private telephone system for electricity undertaking.
T–Transforming station. S.P.—Primary sub-station.

stations can have the telephone installed, and the instrument is plugged in as desired, *e.g.*, when visiting the station. As an undertaking develops, the more important this service becomes and is therefore worthy of adoption in the early stages, Fig. 100.

The use of supervisory control apparatus has increased in popularity, and although it has been limited to indication purposes, no doubt its proved reliability will justify adoption to other functions. The remote control of plant may be carried out by :

(1) Direct pilot wire ; (2) Supervisory control ; and (3) Selector schemes.

Supervisory control necessitates equipment similar to that in use on auto-telephone exchanges and requires only two or three

pilots. Such a system, Fig. 101, is operated over a minimum number of wires, is simple, and inexpensive in installation and maintenance. The following facilities can be provided :

(1) Open and close circuit breakers.
(2) Tap changing operations on transformers and boosters.
(3) Synchronise supplies.
(4) Start and stop rotary and motor convertors.

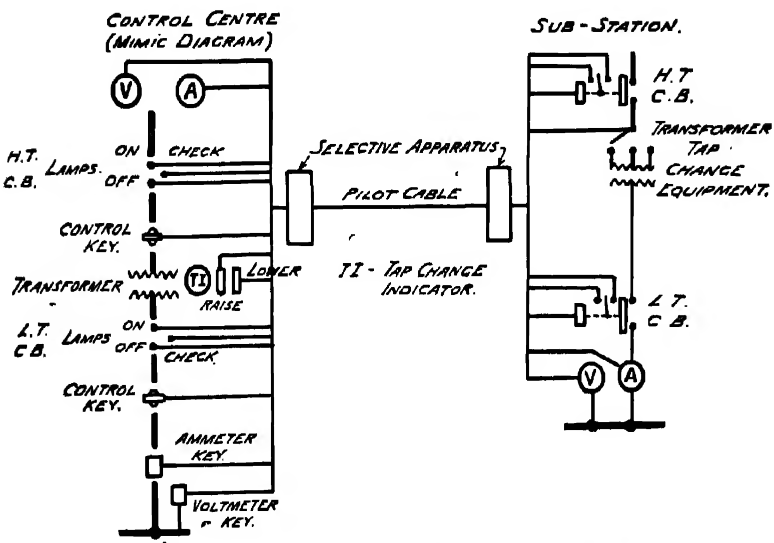


FIG. 101. Simplified diagram of remote supervisory control over pilots.

(5) Switch rectifiers on and off.
(6) Indicate amperes, volts, kVA, power factor, etc.
(7) Telephone communication.
(8) Alarms.
(9) Positional control.

All the facilities normally required can be provided over two pilot wires linking the sub-station to the system control-room. Carrier current can be superimposed on the power lines and thereby dispense with pilot wires entirely. The Midworth Repeater system affords control and remote indications with few pilot wires. It consists of a transmitter and one or more receivers, the latter being in the form of

moving coil milliammeters, scaled to suit the indication required, Fig. 102. The transmitter contains an originating movement which gives the indication required and which it is desired to transmit to the sub-station. The receiver translates the message into variations of an electrical current in a series repeater circuit, which includes the receivers. When the pointer of the transmitter is deflected, a contact is made with one of the arms of the control movement, and this completes one of the field circuits of the control motor which drives the

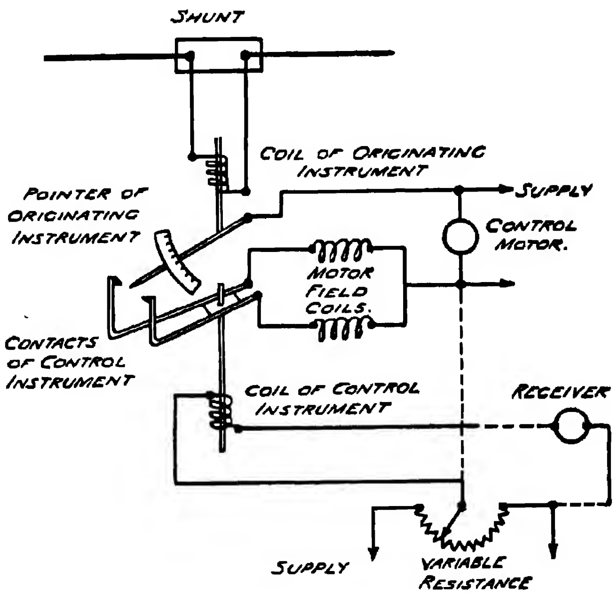


FIG. 102. Midworth repeater system of remote control.

moving arm of the variable resistance unit. The current in the coil of the control movement is therefore altered until its contact arm is deflected so that the pointer of the originating instrument is floating freely between them. The deflection of the pointer of the receiver is the same as that of the control instrument and also of the originating instrument. One pair of pilot wires can be made to do the duty of a number of circuits. Factors influencing the choice of remote control are : distances between sub-stations and control centre ; number of controls and indication required ; cost of pilot cable and its installa-

tion ; cost of control equipment, future developments, and facilities for extensions to the system employed.

The majority of static sub-stations are unattended, therefore some form of low temperature heating with thermostatic control is provided. Where transformers are installed in the same chamber as the switchgear, a portable type radiator will suffice. A disadvantage of wall radiators is that convection air currents draw particles of dust on to the wall and nearby apparatus. Heaters should be placed below the inlet wall grates near the floor of the chamber. Cold air entering the chamber will form a cushion above the warm air, allowing it to rise

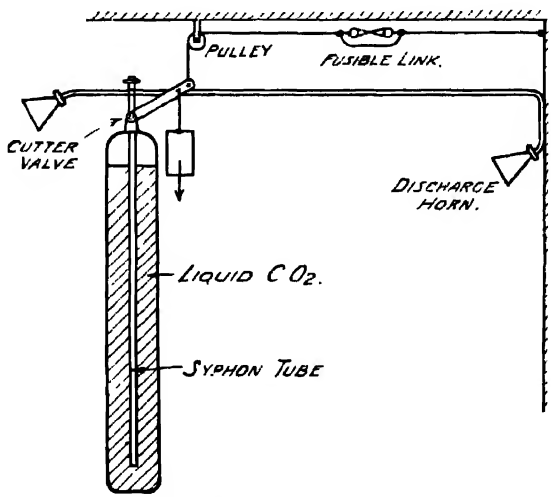


FIG. 103. CO_2 equipment.

gradually and the switchgear is kept dry by means of an ever changing air, rather than through the action of heat.

Chambers in which important relays or meters are installed should be ventilated and heated as the instruments are more prone to damage from moisture than most switchgear.

The number of lighting points to be provided will depend on the size of the chamber, and good general lighting will suffice. A plug-point should be included for a wandering handlamp. The controlling switches should be mounted in accessible positions, preferably near the doors, and two-way switches are found to be convenient. Although good general lighting is normally provided, it is desirable to make

some provision for emergency conditions to facilitate the work of the operating staff, particularly during hours of darkness. Switches and lampholders are usually of the all-insulated Home Office pattern. Iron-clad switches and conduit or Pyrotenax cable are also used. If routine operations or replacements are necessary in outdoor sub-stations during hours of darkness, a permanent installation of flood-lights should be provided. An alternative is to include a series of

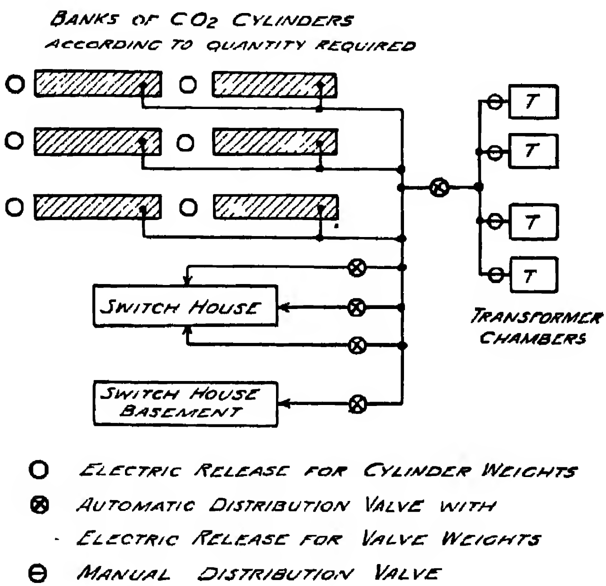


FIG. 104. Fire fighting layout with electric release equipment.

sockets located around the station, which serve a number of portable floodlights. Care is required so that lights are placed to avoid dense shadows and become confused with structures.

The installation of automatic fire-fighting equipment in all but large sub-stations does not appear to be justified. Experience shows that it will suffice if a number of sand buckets and hand equipments are provided. As the size of circuit breaker and transformer capacity increases, it becomes more necessary to install automatic means of extinction. The provision of hand-operated extinguishers is of little use in an unattended sub-station. Flooding with CO_2 gas (Figs. 103

and 104) offers a reliable means of oil-fire extinction in a building, but the water-sprinkler system appears to be preferable for outdoor transformers.

Bibliography

C. C. Barnes. "Cables in Mines," *Electrical Review*, 18th July, 1947.

C. J. Beaver and E. L. Davy. "The High-Pressure Gas-filled Cable," *Journal I.E.E.*, Vol. 91, 1944.

E. A. Beavis and C. W. Schofield. "Bonding and Earthing of S.C. Three-phase P.I.L.C. Cable Installations," *Siemens' Magazine*, April–May, 1944.

B.I.C.C. "High Voltage Cables," *Publication No.* 225 (British Insulated Callender's Cables, Ltd.

T. H. Carr. "Electric Power Stations," Vols. 1 and 2. (Chapman & Hall.)

R. A. Chattock. "Sub-station Equipment, including Automatic Control," *Proceedings I.M.E.A.*, 1922.

A. G. Cooper and H. Carpenter. "Restoration of Supplies—A New Distribution Scheme," *Electrical Times*, 23rd February, 1939.

Report of Electricity Commissioners. "Fire Risks at Generating Stations." (H.M. Stationery Office.)

D. B. Irving. "Cable Terminations," *Journal I.E.E.*, Vol. 92, 1945.

W. Kidd and E. M. S. McWhirter. "Operational Control of Electricity Supply Systems," *J.I.E.E.*, Vol. 92, Part No. 28, 1945.

S. R. Mellonie and W. E. B. Nettleton. "The Design and Maintenance of Transformer Sub-stations for City Areas," *Electrical Power Engineers' Association*, March, 1933.

S. W. Melsom. "Electric Cables and Fire Risks: Recent Developments and Investigations," *Journal I.E.E.*, Vol. 87, 1940.

S. L. Pearce. "Polyphase Sub-stations: Their Equipment and Working," *Proceedings I.M.E.A.*, 1904.

R. N. Pegg. "Planning of City Thoroughfares," *I. Civil E.*, 1944.

L. Romero. "Present-day Practice in A.C. Urban Distribution," *Proceedings I.M.E.A.*, 1934.

G. W. Stubbings. "Power Factor Problems in Electricity Supply" (E. & F. N. Spon).

F. C. Winfield. "Fire Precautions in Major Electrical Stations," *Journal I.E.E.*, Vol. 81, 1937.

CHAPTER V

SWITCHGEAR

Types. The types of switchgear used for sub-station service are as follows :

(1) *Cellular*—in which the components are enclosed in brick, moulded stone, and concrete cells or compartments.

It is usually cheaper than metal-clad units, and modifications may be made without undue interference. The arrangement of components is simple, the majority of which are visible on opening the doors. The busbars being air-insulated minimises fire. Greater building space is necessary, erection costs are higher, and interlocking schemes are more complicated than similar rated metal-clad gear. Unit isolation is as near complete as possible, for both main and control cables can be unitised. The circuit breaker is a fixture, which rather hinders quick replacement. Duplicate busbars facilitate insulator cleaning and testing.

(2) *Cubicle*—in which the components are enclosed in sheet metal cubicles, with or without barriers. The breaker is a fixture, similar to cellular gear. The cubicles are factory built, requiring no elaborate structures and the assembled boards require a comparatively small floor area. A faulty unit may endanger the adjoining units, and the circuit breaker rating is limited. Air blast breakers overcome this disadvantage. The structures are not entirely dust-proof, and regular cleaning of the insulators is necessary. It is comparatively cheap, components can be separately chosen, quick installation, site changes are simple, cable boxes are accessible and maintenance is easy.

(3) *Truck*—in which the circuit breaker is carried on a truck, and can be withdrawn from the frame by wheeling or sliding.

A breaker is easily removed and replaced by a spare unit. Simple interlocking schemes are practicable, but the moving parts must be as light as possible, thus restricting the size of breaker. The cost is higher than that of cubicle gear and more floor space is required. Truck and cubicle types are not recommended where they cannot be made dead for cleaning and inspection.

(4) *Metal-clad*—in which all conductors and insulation are enclosed in an earthed metal case.

Air insulation for busbars and chambers is usual for medium voltages except in special cases, and for mining service, where compound

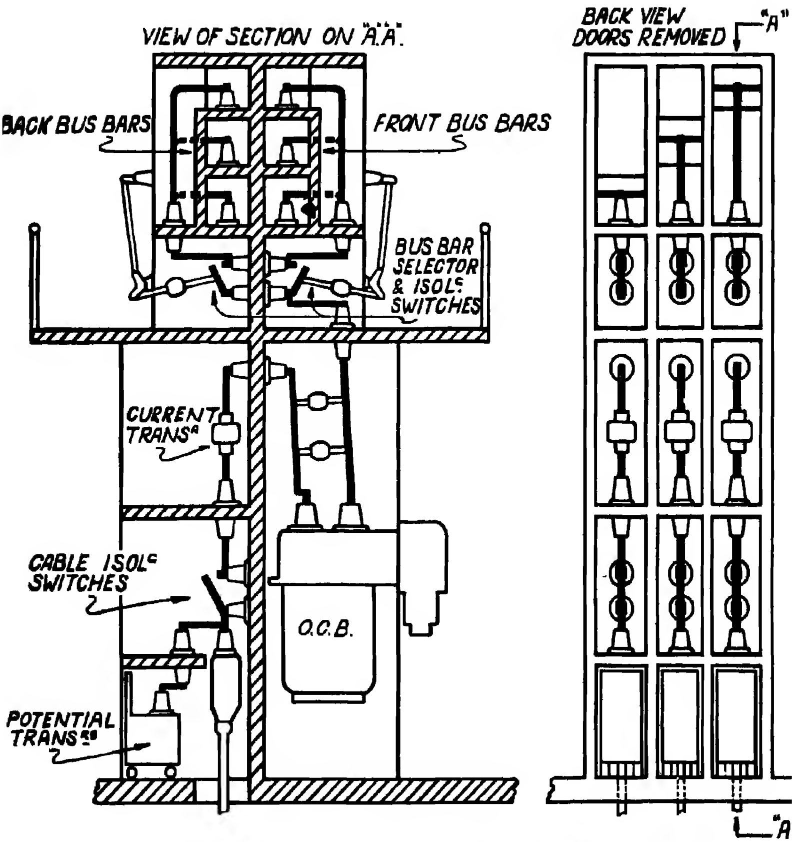


FIG. 105. Stone cellular switchgear showing single feeder and double busbar (B.T.H. Co.).

filling is the practice. Compound and oil fillings are used on higher voltages. The units are very compact as the electrical clearances are reduced by the use of compound and oil fillings. By enclosing all parts in a substantial metal shell, the gear is vermin, moisture, and, to some degree, fire-proof. It is a factory built unit with consequent

reduction in site work. The cost is generally higher than other types of similar ratings, but it has the advantage of being almost fool-proof, since simple and efficient interlocks can be used. There are two principal types—horizontal isolation and vertical isolation, the latter being

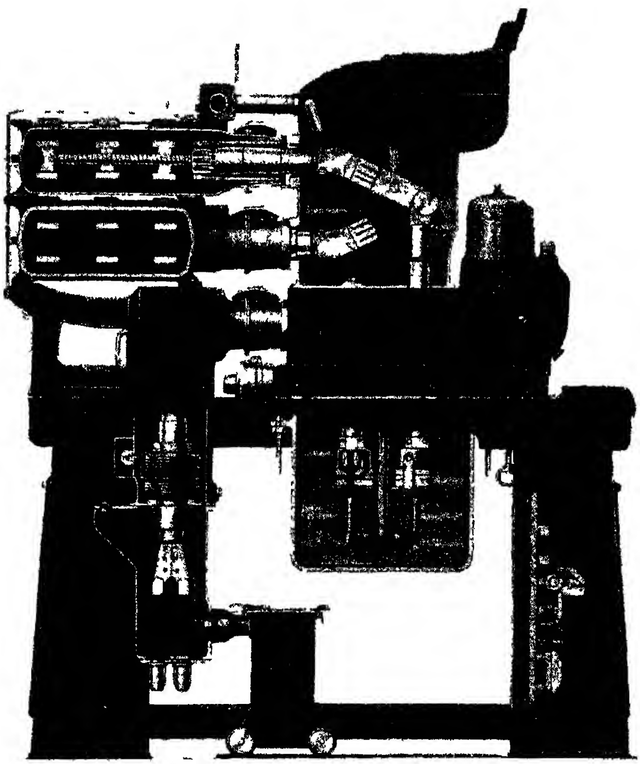


FIG. 106. Cross-section of typical duplicate busbar horizontal draw-out metal-clad equipment with off-load selector switch (Metropolitan-Vickers Elec. Co.).

favoured for higher voltages. There is considerable saving in floor space, a minimum number of loops and bends giving a stronger arrangement of conductors to withstand electro-magnetic forces ; facilitates duplicate circuit breaker layouts, and inspection is possible

without encroaching on passageway. Metal-clad gear is also used for outdoor working.

(5) *Outdoor* (*Open*)—has been more widely adopted for primary sub-stations, and especially those for the " Grid " system.

Buildings are unnecessary, except those required for the control equipments and stores. The units being in the open, require more general maintenance and are liable to damage from lightning, fouling from windswept twigs, and birds, etc. Wide spacing is necessary, which entails a larger ground area, whilst in some localities deterioration of insulation may be experienced due to pollution of the atmosphere, especially where salt and soot are present.

(6) *Air blast*—in which air under pressure is applied to assist in the making and breaking of the circuit, and also afford the desired degree of insulation within the chamber.

The air blast breaker functions with air at a pressure of about 140 p.s.i., since at this pressure its dielectric strength is comparable with switch oil. Air pressures of from 135 to 200 p.s.i. are in use.

The space occupied compares favourably with standard switchgear, and maintenance is said to be simpler and cheaper. It is only to be expected that this type will find application for sub-station service, since it can be adapted to either indoor or outdoor working. It is adaptable to cellular, cubicle, or truck types, and has the advantages of freedom from explosion and fire. It is suitable for service requiring frequent operation (furnaces, etc.) ; is more rapid and adaptable for reclosing than oil-filled gear and is expected to prove less costly for higher voltages and rupturing duties at present limited to 11 kV and above.

(7) *Air break isolators*—which are used with cellular, cubicle and truck types, also where two feeders are supplied from one circuit breaker. Neutral earthing equipment is another application.

The breaking capacity is dependent upon two factors : (*a*) The atmospheric conditions in the enclosure, and (*b*) the speed of operation. The operation is dependent entirely on the human element and it is possible therefore for the opening operation to be slow and hence to cause an acute system disturbance at the instant of opening. The conditions obtaining when opening a circuit containing capacity may be analogous to that when a circuit breaker is clearing a short circuit current when protecting a line of appreciable capacity. Under these conditions, should the contacts open at the instant of current zero then the stored energy due to the capacitance of the line will discharge through

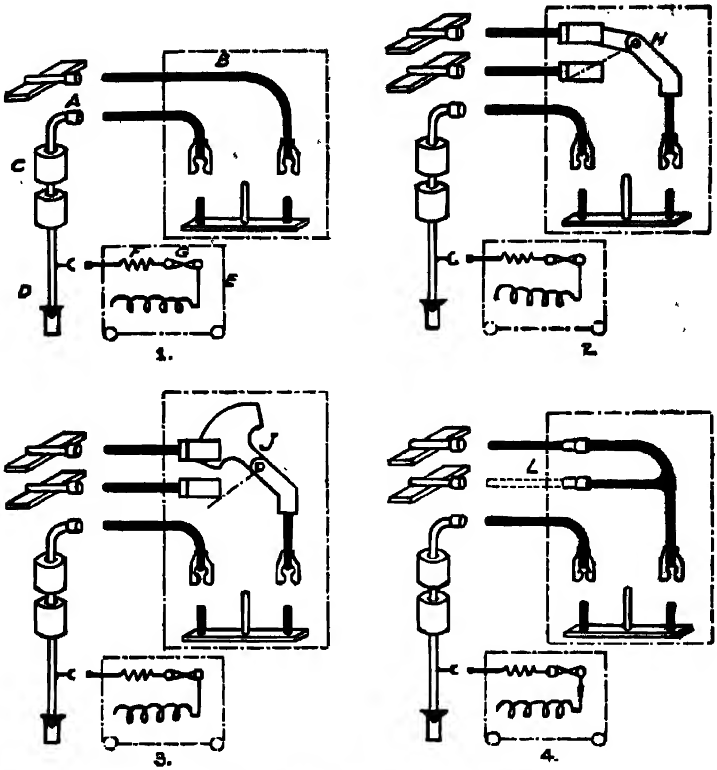


FIG. 107. Methods of busbar selection.

A—Isolating plug and socket.
B—Withdrawable circuit breaker.
C—Current and protective transformers.
D—Feeder cable.
E—Withdrawable voltage transformer.
F—Limiting resistance.
G—High tension fuse.
H—Selector switch, off-load change.
J—Selector switch, on-load change.
L—Selection plug, off-load change.
(1) Single bus.
(2) Duplicate bus with off-load selector switch.
(3) Duplicate bus with on-load selector switch.
(4) Duplicate bus with removable plugs.

the closed circuit formed by the inductance and capacitance in series, thereby inducing a high frequency transient voltage on the system. Opening of the isolator on the very instant when the transient condition resulting from this action would create the greatest disturbance by raising the voltage to a value many times in excess of normal working voltage, a breakdown resulting at a point where live metal is nearest to earth.

They are generally of the off-load type, but it is sometimes necessary to break the line charging current, and they should be capable of this duty. The limiting value of the leading current at zero power factor which can be safely broken depends on the system voltage. Such isolators should not break a leading current of zero power factor if it exceeds 2 to 4 amperes on 11 and 6·6 kV systems. The difficulty is not so much the persistence of the arc, as the danger of the arc flashing over to adjacent earthed metal. If the isolators are enclosed in sheet steel cubicles, then the possibility of flashing over to the steel platework is the limiting factor. Where the length of line connected is considerable, or where higher voltage cable is used, air-break isolators may be unsafe to operate and oil-immersed isolators are preferable. Wherever possible, and particularly where large fault currents obtain, the isolators or links should be so arranged that the electro-magnetic forces tend to hold them in the closed position. The alternative is to use locking hooks or pins to prevent opening during fault conditions.

When opening lower voltage air break isolators it is advisable not to break magnetising current as a persistent arc can be established.

(8) *Air breakers*—which are used for outdoor sub-stations, being mainly employed for the sectionalising of lines and busbars, tapping points, etc.

Various types are in use, and to give long and effective service out of doors the breaker must give guaranteed operation under all weather conditions, be exceptionally robust, and require little maintenance. Arcing horns are fitted, the shape and diameter of which play an important part in the breaker operation. The arc will strike and maintain itself longer with small diameter horns than with the larger sizes, and for this reason the latter are preferable. Adequate spill-over surface and safety factor on insulators are desirable to allow for weather conditions. The method of connection should augment the blow-out effect by assisting the arc up the horns against downward wind pressure.

(9) *Air-Break Circuit Breakers*—have been in existence for many years but have never enjoyed much favour, possibly due to the lack of

high power testing facilities. The arc chute is a packet of iron plates spaced a small distance apart and designed to move the arc upwards, split it, lengthen it—increasing its resistance rapidly, cool and deionise it until at an early current zero arcing cannot continue due to the build up of insulation overcoming the rise of voltage. In order to reduce the size, high-pressure, silver-faced line contacts have been perfected for carrying large continuous currents and occupying very little space.

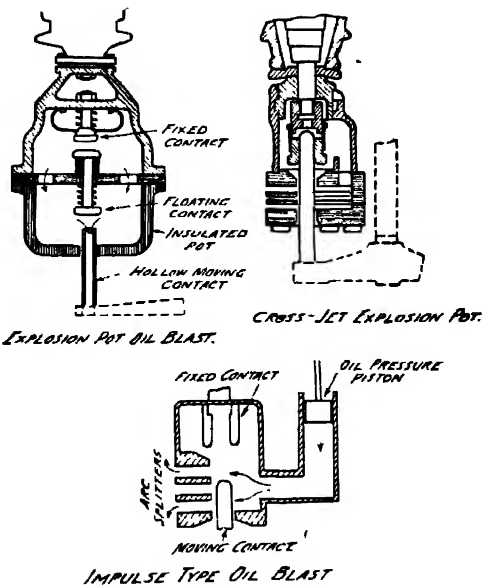


FIG. 108. Typical oil circuit breaker contacts.

These contacts have to be protected from damage by high-pressure arc-resisting alloy arcing contacts which make and break after the silver-faced contacts. These breakers are available in this country up to 660 V, having two ratings :, 25 M.V.A. at 400 V and 15 M.V.A. at 400 V and at 3,000 V rated at 150 M.V.A. The advantages claimed for these are cleanliness of operation and maintenance ; ease of inspection and maintenance ; reduced contact wear ; mechanical freedom of movement and fire-fighting equipment is not essential. They are, however, relatively expensive to produce. In America they are marketed at 15 kV and 500 M.V.A. American rating.

(10) *Fusegear*—in which open busbars, fuses and isolators are mounted on framework, or, alternatively, enclosed in cast iron or steel-plate boxes.

Such equipments are limited to low and medium voltages and have generally proved satisfactory. Troubles have been experienced on heavily loaded circuits where cookers predominated, which resulted in overheating without the fuses blowing since it is more of a " creeping " load of sustained character.

TABLE. 12. *Typical Switchgear Voltages and Rupturing Capacities*

Type	Voltage kV	Rupturing capacity M V.A
Cellular (stonework or concrete) .	33·0 2·2	1,500 350
Cubicle (steelplate)	15·0 6·6 0·4	350 150 10
Truck	15·0 0·4	250 10
Metal-clad (oil-filled) . .	132·0 66·0 (O.D.) 33·0	2,500 1,500 1,000
Metal-clad (compound-filled) . .	33·0 0·4	1,000 25
Air blast	132·0 3·3	1,500 150
Fusegear	0·6 0·4	35 25

Oil-immersed switch-fuses are sometimes used for underground (street-pit type) transformers and trouble is experienced with fuse materials. Pure tin wire appears to give the most satisfactory service,

since lead and copper wires corrode very rapidly if they have to carry unduly heavy currents. A 22 S.W.G. pure tin wire fuses at about 10 amps. in air but will carry some 30 amps. under oil at 60° F.

Pole-mounted and small distribution transformers are usually protected by fuses on the incoming side, the tetrachloride type being popular. The element, which is spring-loaded, is placed in a glass

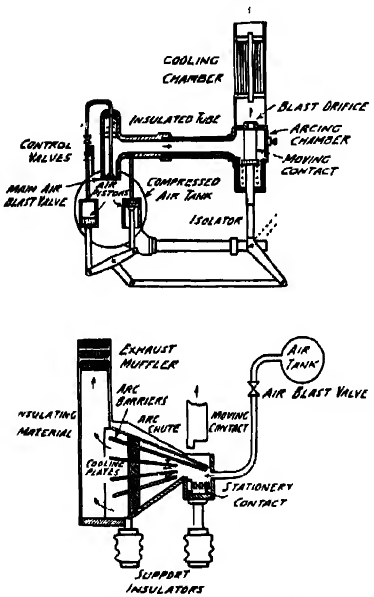


FIG. 109. Typical air blast circuit breakers.

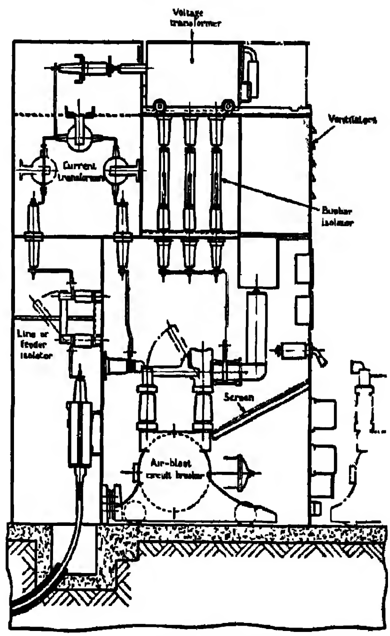


FIG. 110. 11 kV 500 M.V.A. air-blast circuit breaker equipment. (English Electric Co.)

tube containing carbon tetrachloride and when the element melts the spring pulls it apart and the liquid quenches the arc.

The pull-down type of higher voltage switch is convenient as fuse replacement is safe. In districts subject to lightning the silver fuse wire appears to be the most suitable and experience has shown it to possess the necessary stability under normal load conditions. The lower voltage fuses can be accommodated in a locked cabinet within reach from ground level. Three maximum demand indicators operated from 100/5 A ring type current transformers can also be included.

Figs. 105–113 show typical circuit breaker and fuse details and layouts.

An oil circuit breaker requires a tank to hold the oil and one method of classification divides them into earthed-tank and live-tank breakers. A further sub-division is single-break and double- (or multi-) break

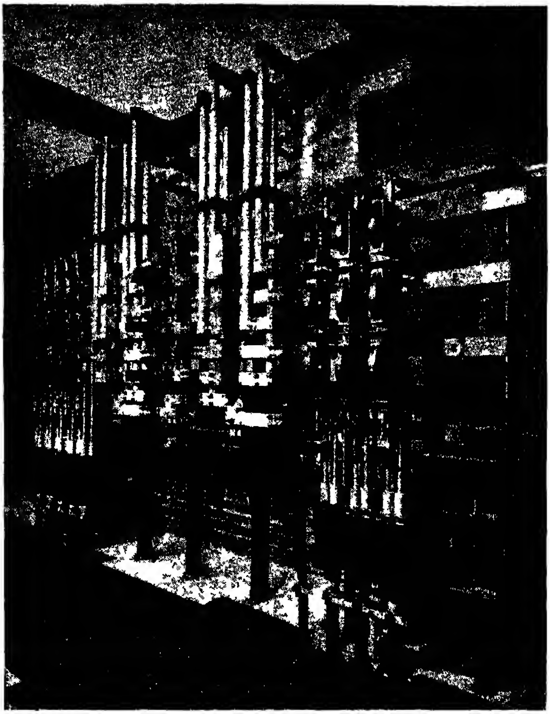


FIG. 111. 400 V 4-wire fuse board arranged for 2–1,500 kVA transformers (English Elec Co.).

units. The single-break units may also be of the vertical or horizontal types. In the live-tank type, the oil only performs the interrupting function as the main insulation to earth is provided by insulating supports.

Circuit Breaker Rating. The B.S.S. 116—1937 outlines the recognised present-day standard, and four ratings are given :

(1) Symmetrical breaking capacity.

(2) Asymmetrical breaking capacity.
(3) Making current.
(4) Short-time current.

One of the most important factors is the overall, or total clearance time from inception of fault to final arc extinction, and this time includes the relay and mechanism times. On large systems, high-speed breakers are often fitted with high-speed relays, but even then the clearance time is quite a few cycles. This feature is important, for the asymmetrical current depends on the total time and not the arcing time. The maximum short-circuit M.V.A. which a circuit breaker can

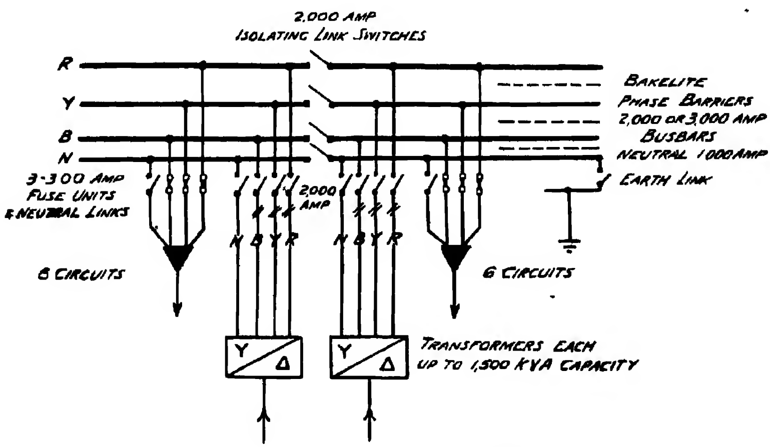


FIG. 112. 3-phase 4-wire open type sub-station board.

deal with depends primarily on the current it can break. The upper limit is probably in the region of 45,000 amperes, so that for a working voltage of 6 kV the maximum breaking capacity would be :

$$= \frac{\sqrt{3}.\ 6.\ 45{,}000}{1{,}000} = 470\ ;\ \text{say, } 500 \text{ M.V.A.}$$

Circuit breakers of 1,500 M.V.A. at 6·6 kV are in service and have proved satisfactory. The upper limits are fixed by economic rather than technical considerations. At voltages of 33 and 66 kV such heavy currents are rarely met with, and the limit is about 1,500 M.V.A. Another factor to be considered is the maximum making capacity of

the breaker. If the current to be broken is 45,000 amperes, then the possible making current, if the breaker is closed on to a fault, will be: $1{\cdot}4.\ 1{\cdot}8.\ 45{,}000 = 114{,}000$ amperes. The factor 1·4 allows for the peak value of the sine wave, and the factor 1·8 allows for the possibility of an asymmetrical current wave. The breaking of magnetising and charging currents of large magnitude may impose abnormal voltage stresses on circuit breakers and other apparatus. The making capacity value for remote electrically-operated circuit breakers is based on the assumption that 100 per cent. of the D.C. supply is available at the solenoid closing coils. It is difficult to assess a making capacity value to direct manually-operated breakers, for so much depends upon the manner in which the closing operation is performed. The need for

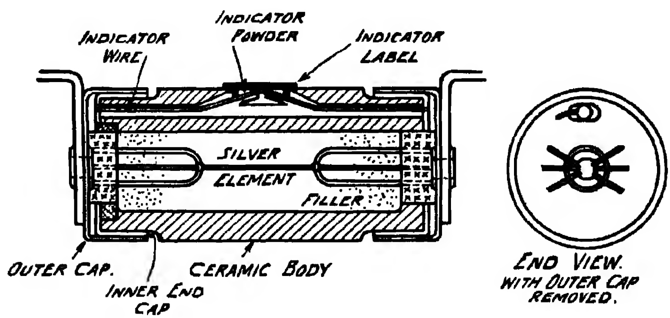


FIG. 113. H.R.C. cartridge fuse (G.E.C.).

power closing of breakers is appreciated, and for this reason mechanical devices such as spring-operated closing mechanisms are superseding the hand-closing arrangement for circuit breakers of 150 M.V.A. and above. It is desirable to maintain the closing coil voltage within prescribed limits, for a high voltage (10 to 15 per cent.) may overstress the breaker mechanism.

For lower and medium voltage switchgear present-day limits are of the order of 25 to 35 M.V.A.

Design and Constructional Details. With the information made available through the medium of testing stations, designs are being standardised and new features are thoroughly proved. Some of the principal features of design are :

(1) Contacts and current carrying conductors should be capable of withstanding maximum fault current.

(2) Contacts should be such that contact pressure is improved with fault current flowing.

(3) Conductors should be proportioned to withstand any electromechanical forces.

(4) Operating mechanisms should be capable of withstanding the throw-off forces due to electro-magnetic effects.

(5) The supporting framework and standards should withstand all mechanical forces, and cast iron should be in compression, mild steel being used to resist tensile forces. Conductor arrangements should be such that loop formations are a minimum.

(6) The closing device—solenoid, pneumatic, etc.—should have adequate power to close positively and rapidly against any electromagnetic forces. Pneumatic operation is more rapid than electrical operation.

A circuit breaker has to withstand the effects of arc energy and mechanical and thermal effects, and the factors which enable it to deal with these are :

(*a*) Speed of break ; (*b*) Number of breaks per phase ; (*c*) Length of break ; (*d*) Head of oil ; (*e*) Volume of air cushion ; (*f*) Venting arrangements ; (*g*) Tank construction ; (*h*) Electrical clearances in air and oil ; (*i*) Arrangement and strength of conductors.

The air space above the oil should be such that any gases formed during one operation are too rich to be ignited by the heat generated at subsequent operations, and thus reduce the explosion hazard. Contacts vary in design, and explosion pots are generally fitted on the higher-rated units. The breaker tanks are of mild steel boiler-plate, the top plates being of cast iron, cast steel, malleable iron, bronze or welded steel boiler-plate, according to the current rating and rupturing capacity. Non-magnetic inserts in steel covers reduce hysteresis losses. Tank lining may be elephantide, plywood, or similar material. Steel-plate phase barriers, slotted, and extending across the tank, form a continuous metal barrier between phases below oil, and shield the arcs magnetically and increase the tank strength. Oil, compound-filled, and condenser bushing type busbars are used for the higher voltages, bushings being tested by means of a Schering Bridge for power factor loss. Isolating devices should be interlocked with the corresponding breaker so that they cannot be operated until the breaker is opened. Special testing sockets are included and in many designs primary injection tests are possible. Voltage transformers should be connected in the protected zones with which they are associated and be

arranged to avoid risk of danger to the operator. Megger, current and voltage tests may also be provided for. Earthing devices should be provided, and safe and reliable procedure should provide :

(*a*) Effective earthing operations by means of extension contacts on the circuit breaker, thus enabling the operation to be done through the breaker and so affording protection to the operator.

(*b*) Feeder and busbar shutters arranged for separate control, so that " live " spouts can be protected while carrying out tests on dead conductors or working nearby.

Sub-station switchgear up to 150 M.V.A. rupturing capacity is generally manually operated, but at and above this rating spring-closing or electrical solenoid operation is recommended. With electrical operation the operating switches, instruments and protective relays are mounted on control boards which are placed in a separate room. Although this is expensive the cost is justified on primary sub-stations.

With rectifier switchgear, the rupturing capacity is of especial importance, since a severe back-fire is virtually a short-circuit across the secondary of the transformer, and should the higher voltage breaker fail to isolate the rectifier from the busbars and the breaker contacts weld together, an explosion may result.

Explosions resulting in fire have occurred in certain types of switchgear when isolating the circuit breaker from a live busbar some time after clearing a fault. An explosive gas in the busbar spouts is ignited by the capacity current spark which occurs at the isolating contacts when lowering a circuit breaker from a live busbar. The ignition of the gas and the associated flame causes a flashover from the live busbar isolating contacts in the spouts to the surrounding earthed metalwork.

Maintenance. A rigid programme should be formulated and adhered to, the results being recorded, particularly those concerning : adjustments or replacements, items inspected and tested, engineer responsible and date. Maintenance may be broadly divided into two sections :

(1) Electrical—which includes insulation, current capacity, arc control and extinction.

(2) Mechanical—which includes physical operation of the various components.

Above 11 kV, periodic power factor tests on all insulation is suggested, and accurate records will indicate any deterioration in insulation of bushings, separators, and post insulators, etc. The cleaning and

inspection of higher voltage switchgear requires special care in order that it is made safe to work on. The procedure will generally be as follows :

(1) Open circuit breaker, and isolate.
(2) Apply voltage indicator.
(3) Apply earthing device.
(4) Touch by hand.

Much will depend on the type of switchgear installed, and the facilities provided vary.

Flashovers have occurred on 33 kV switchgear due to water gaining access to the circuit breaker tank by way of deteriorated gaskets on the top plate. The water had accumulated in the tank bottom and had been absorbed by the insulated lining which had disintegrated and a lamination had possibly bridged the gap to the arc control device. Regular tests should be made on the oil in all outdoor switchgear and it is also desirable that linings of a porous nature should terminate 1 in. or so from the bottom of the tank outside the area where free water might occur.

Mining Switchgear. The coal mines regulations lay down rules as to the control of all electrical circuits, and reliable automatic tripping gear must be provided in the switchgear to deal effectively with over-current, earth leakage, and other faults, and to efficiently earth the circuits when apparatus is made " dead ". For mining service underground there are special requirements additional to those normally specified for surface plant. The apparatus must be flame-proof (Fig. 114), specially robust, easily accessible for adjustment or renewal, simple to clean and maintain, of limited height and weight, and suitable for service in damp situations. The performance required from flame-proof enclosures of electrical apparatus is defined in B.S.S. 229—1940, and this specification also outlines those features in design and construction which are considered essential or desirable.

Various designs of fast locking doors have been tried and some have proved more successful than others. The advantages and inconveniences of the door with bolts are well known and this arrangement while being mechanically simple does not coincide with the miners' point of view. It takes a long time to open and close the door owing to the numerous bolts ; the door is heavy and there is a possibility when replacing it of injuring some thread of the bolts and losing some nuts. In the mine the atmosphere is heavily loaded with dust and moisture, and the effect on the threads is that the nuts, quite often, cannot be

put back into place in the correct way. Inspection and maintenance may be impaired due to this inconvenience. The single-bolt action

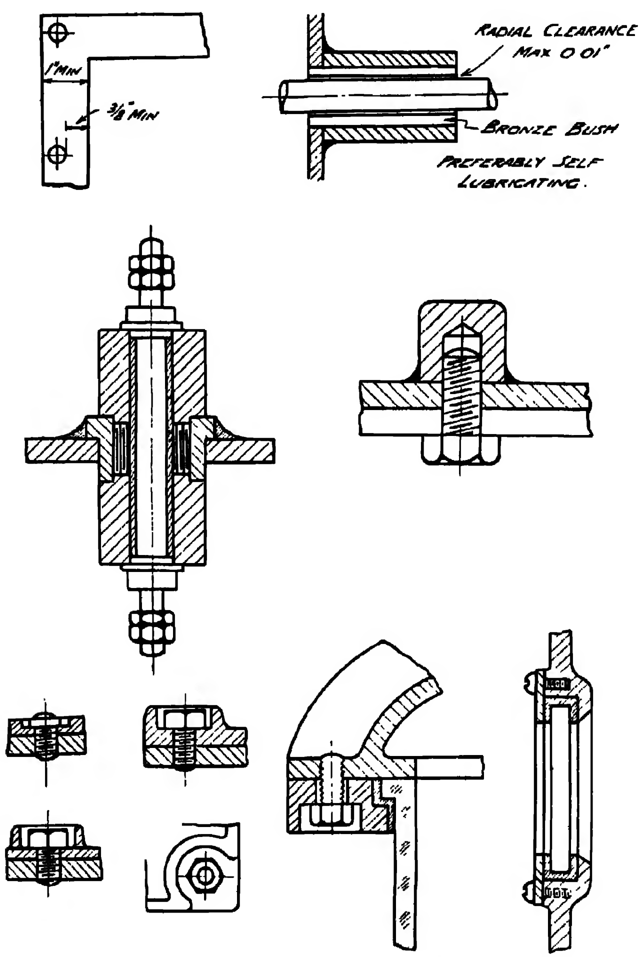


FIG. 114. Mining switchgear details.

locking door overcomes these difficulties, the action on a lever provides the closing of the door and this may be operated only with a sepcial key which can be used only by qualified personnel. A descrip-

tion of one type will be found in the *Mining Electrical and Mechanical Engineer*, September, 1948, in a paper by G. F. Douheret.

The fabricated sheet steel or boiler-plate enclosure is preferred in those cases where it is necessary to withstand a high internal hydraulic pressure of, say, 100 p.s.i., and also in situations where falls of stone are likely, for cast iron casings fracture more easily. A disadvantage of the prefabricated enclosure is that under some conditions the plate tends to flake or corrode, whereas a casting is unaffected. In a corrosive atmosphere, for surface working, *e.g.*, coke oven or gas producer fumes, castings are preferable. On flameproof apparatus, the air spaces in busbar chambers, switch top plates, cable dividing boxes, etc., should all be filled solid with compound, so that no space is available for the accumulation of gas. Terminal cable connections to busbars inside air-filled chambers should be avoided in those cases where the design is such that it is necessary to remove a lid to unfasten terminals to which the cable is connected.

The oil-immersed circuit breaker with compound filled busbar chambers and either horizontal or vertical self-isolating feature, is usual for distribution purposes underground, where switchgear is fixed in permanent positions. Where the district sub-station has to be moved from time to time removable dividing boxes are provided. The joints between top plates and tanks should be machine faced and have no measurable gap between the flanges. The two principles involved in design are strength of structure and width and length of openings. Whilst the oil-immersed circuit breaker is preferable whenever possible, the air-break type is preferred for coal face machinery. It is adaptable to remote control and suited to frequent starting and stopping, which is required for coal cutters, conveyors, loaders and drills. When employed in damp situations, full reliance is placed on sound insulation. The oil-immersed breaker has an advantage in that oil is always present as an insulating medium, whereas the air-breaker is exposed. Air-breakers working in damp places should have their interiors removed at regular intervals for cleaning and drying. The loads at the coal face vary from 5 to 60 B.H.P. and do not require heavy switchgear, and the rupturing capacities on the lower voltage sides of the transformers near the coal face is relatively small compared with that on distribution switchboards near the shaft.

Switchgear Control. With electrical or pneumatic operation of switchgear it is essential to provide at least one battery, but in primary sub-stations two may be justifiable. When D.C. is only required for

switchgear closing and tripping, emergency lighting, and small auxiliaries, the capacity of the battery will be determined by an assumed proportion of circuit breakers closing simultaneously. When two batteries are provided, arrangements are made to carry the load with one while the other is being charged. When switchgear tripping only is desired a much smaller battery is required. For pneumatic operation it is necessary to provide an air compressor, air receiver, and the usual auxiliaries associated therewith.

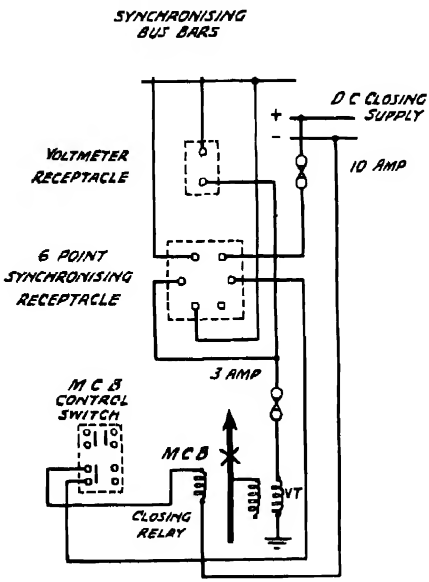


FIG. 115. Control panel synchronising connections.

Spring operating gear normally compressed by a small motor with provision for manual compression is in use, the spring being released by a small 60 V battery. Solenoid closing mechanism operated by metal rectifiers of the selenium-iron type is also used. Some engineers do not favour large batteries for solenoid operation. Local control of a circuit breaker is provided in addition to remote control in the control room.

Each circuit breaker equipment should have a control panel upon which are mounted the operating and indicating devices, together with the necessary instruments and protective relays. All control switches should be designed to avoid inadvertent operation, with provision for locking in the open and closed positions. Where synchronising apparatus is included, the connections between the control switch and closing relay coil of the circuit breaker should be completed through a receptacle, Fig. 115, bridge by a synchronising plug, so that it is impossible to close the breaker until the plug is inserted in its corresponding synchronising receptacle. An indicating panel may be mounted at the top of the control panel to show automatically, by means of lamps or semaphores, the positions of the associated circuit breaker and

isolators. The indicating panel should include in diagram form the main electrical connections of the equipment it controls. Auxiliary busbars extending throughout the length of each control board should serve the following :

Synchronising connections (A.C.).
Tripping circuit (D.C.).
Closing circuit (D.C.).
Alarm circuit (D.C.).
Pilot lamp indication (A.C. or D.C.).

Each control panel is supplied from these busbars through fuses, Figs. 116 and 117. Probably the best way of ensuring supply to the tripping circuits is to have links in the individual panels, instead of fuses. Both fuses and links are used, but the latter appear to have decided advantages. On one very large system the tripping circuits are not fused and in no case has a totally discharged battery resulted. Battery connections to the circuit breakers where fused should be done so outside the circuit breaker zone so that in case of fire or failure there is no likelihood of the battery being discharged and thus putting out of operation all the other circuits. Terminal blocks should be mounted in each panel to serve all multi-core and other auxiliary cables. A common local alarm bell or a remote alarm equipment gives audible warning in the event of a circuit breaker tripping automatically. A lamp is included in each panel, which shows when the breaker is tripped automatically, and in this way the sub-station engineer will readily ascertain which circuit is open and take steps to restore supply. An alternative is a neon lamp connected across the protective relay

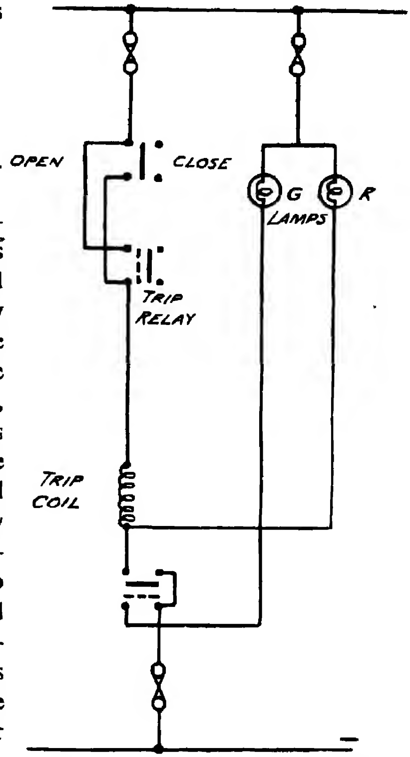


FIG. 116. Tripping and lamp circuits.

terminals of the corresponding trip circuit. The lamp is shorted when the relay operates, and serves to indicate the circuit breaker affected. The lamp current is insufficient to operate the breaker trip coil, but the lamp glows with full brilliance if battery voltage is normal. Red and green lamps indicate circuit breaker in closed and open positions.

All instruments and apparatus for control panel mounting should be back-connected and have terminals and removable links to permit of connecting portable testing sets. It is possible to connect the am-

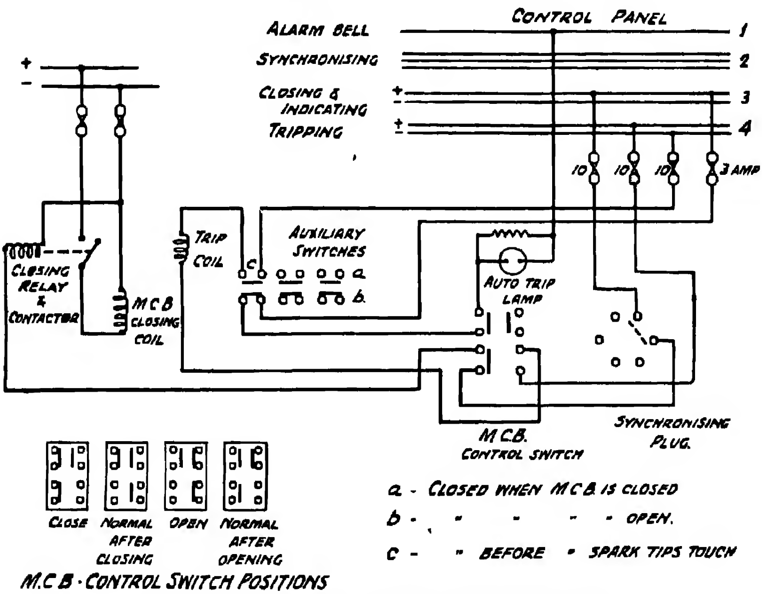


FIG. 117. Switchgear closing and tripping circuits.

meter to measure the current flowing in any of the three phases. Synchronising is carried out between voltage transformers installed in the feeder equipments on the side of the circuit breakers remote from the busbars. Synchronising voltmeters, rotary synchroscope and lamps are included, and the voltmeters are connected by way of the synchronising plug, or voltmeter plug, to any panel equipped with a synchronising voltage transformer. The four conditions required to produce a state of synchronism are :

(1) Running (busbar) and incoming line or set voltages should be the same.

(2) Frequency of the two supplies should be the same.

(3) Phase angle between the (running and incoming) two supplies should be zero—the two voltages are opposite.

(4) Phase rotation should be the same.

A useful feature is an ammeter for the D.C. closing circuit of the

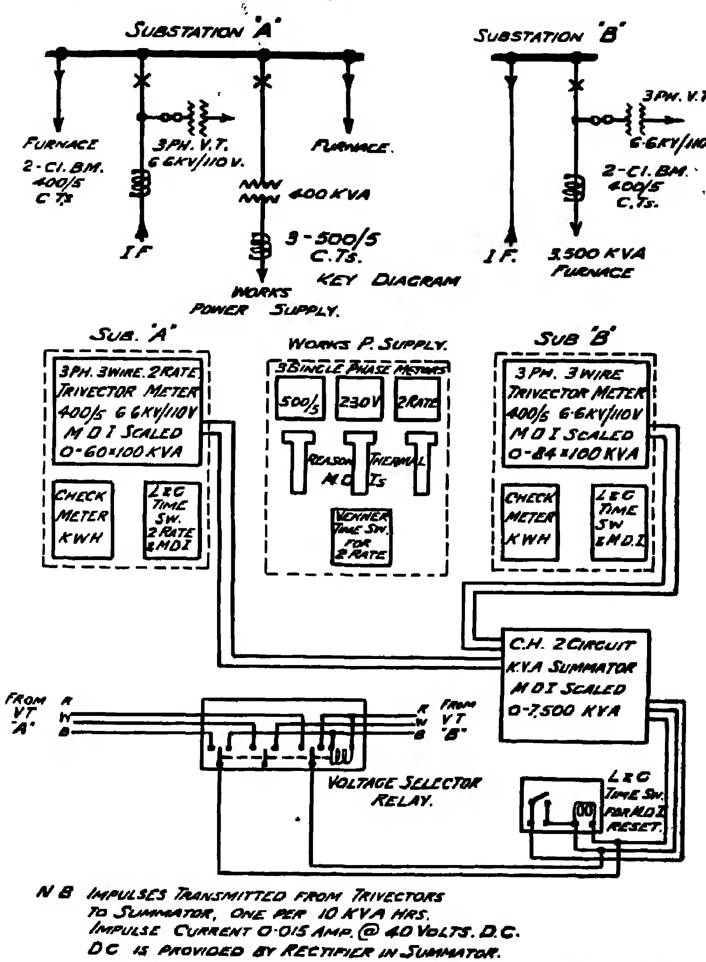


FIG. 118. Metering equipment for summation of works' sub-station loads.

switchgear. An ammeter is provided for each closing circuit, one per annexe or section of switchgear, and should the closing relay contactor

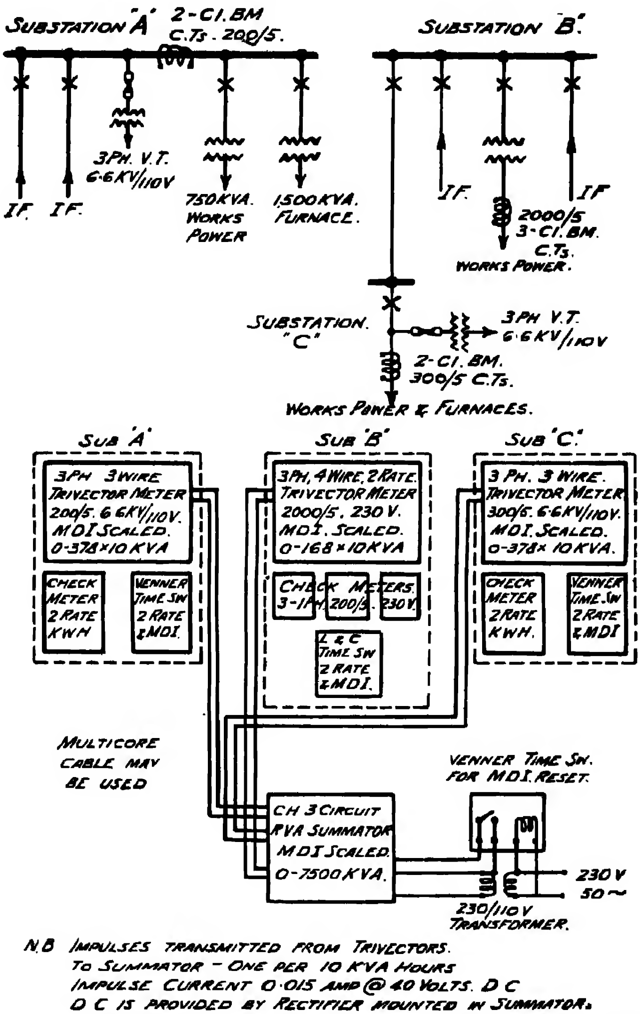


FIG. 119. Metering equipment for summation of works' sub-station loads.

stick in the " close" position, the ammeter shows the closing coil energised. The engineer can then cut off the closing-circuit supply, as the

coils are only short-time rated and a burn-out should result. The closing and tripping currents depend upon the switchgear mechanism and the battery voltage.

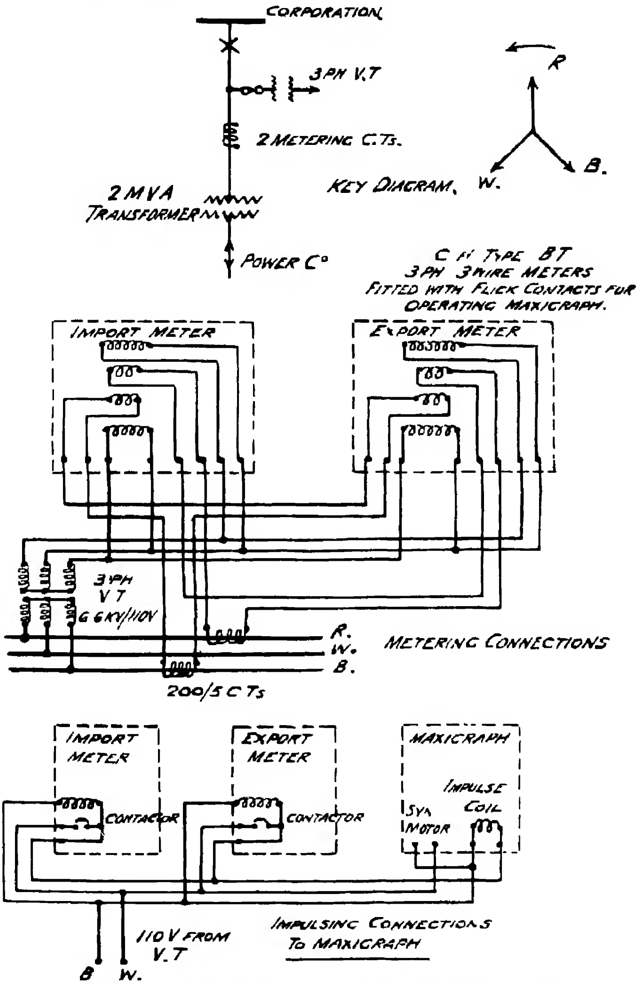


FIG. 120. Metering equipment for interchange of supplies.

Metering Equipment. Metering equipment is required in almost every class of sub-station, and the types and methods of mounting

vary. If a primary or secondary sub-station is interconnected with another supply authority's system, it will be necessary to provide metering equipment for either the import or export of power or both. The feeders for the import and export of power have arrangements for changeover from import to export or *vice versa* as desired.

If a works takes a supply at more than one point it may be necessary to include summation metering to obtain the true maximum demand taken. The method of charging will dictate the type of metering equipment to be installed, and Figs. 118–121 give some idea of the apparatus required. Two thermal demand indicators which are used for sub-stations are shown in Figs. 122 and 123. The practice of one large authority for 400 V supplies is to use three current trans-

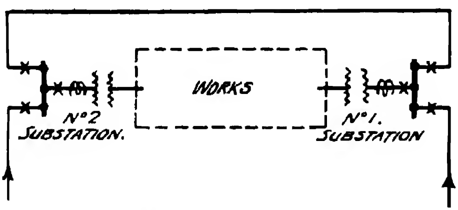


FIG. 121. Duplicate supplies to works.

Supply is metered on H.V. side, the meters being summated for the two sub-stations.

On metering circuit there are also a power factor meter and a recording ammeter for checking the overall power factor and the maximum demand.

The M.V. sides are interconnected and maintenance and inspection are facilitated by changeover arrangements.

formers, three single-phase kWh meters and one or three thermal demand indicators, depending on the tariff adopted. Where special night and week-end rates are in force, three further meters and a time switch are added. In these cases the main meters are energised the whole time to read kWh, the other set having their voltage coils energised during the period of cheap rates only, resulting in a simpler time switch. Fuses are not inserted in the voltage coils, and burning-out of the coils has been experienced. 11 kV supplies are metered in a similar manner, with the inclusion of a three-phase voltage transformer. Large supplies necessitating a kVA demand charge have the demand measured by a Merz-type indicator ; the three current transformers are retained with three single-phase kWh meters which serve as a check on a faulty current transformer which may otherwise remain unnoticed. The exception to the three-meter method is in registering the

kWh's to the 6·6 and 11 kV systems from the 66 and 33 kV systems. Here the two-wattmeter method is used; this gives a guide to the average power factor. Where duplicate transformers are installed, with two 400 V points of supply, each of the latter is provided with three current transformers, each of which is associated with a single-phase kWh meter. One set of summation demand indicators are installed, thus a check on a faulty current transformer is still obtained, an idea of the relative use of the two supplies is provided, and the true maximum demand is recorded. At all 66 and 33 kV sub-stations duplex recorders are installed and major sub-stations are attended and half-hourly readings are logged.

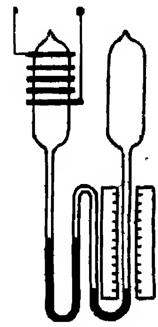


FIG. 122. Thermal M.D. indicator (Reason M.C.)

The "P. & B." type is used for obtaining feeder maximum demands, and is essentially an ammeter with two pointers, one of which is moved over the scale by the other according to the demand on the circuit, and stays "put" at the maximum recorded. The liquid type has two principal parts—a hermetically sealed tube containing air and a liquid, and a short length of coiled conductor of slightly higher resistance than copper. The passage of current through the conductor, which surrounds one end of the hermetically sealed tube, produces heat which expands the air inside the tube. The expanded air in turn forces a

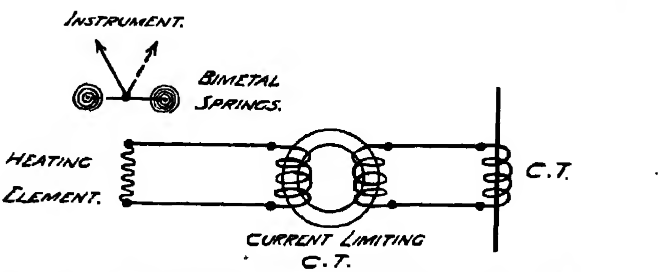


FIG. 123. Thermal maximum demand indicator (P. & B. type).

portion of the liquid into the adjoining tube, where it remains until the instrument is re-set by hand. The amount of liquid carried over is proportional to the current passing. The second tube is graduated, or calibrated, according to scale of charging required—usually in amperes. It is very simple and gives but little trouble, although the

temperature of the room and the condition of the conductor may affect its operation. Time delays of from ten to thirty minutes, Fig. 124, are usual with the demand indicators described. Re-active kVA indicators are balanced load instruments (Fig. 125) and are scaled on both sides of zero, *i.e.*, lag and lead. The idle current ammeter is a similar instrument, except that the scale is marked in amperes instead

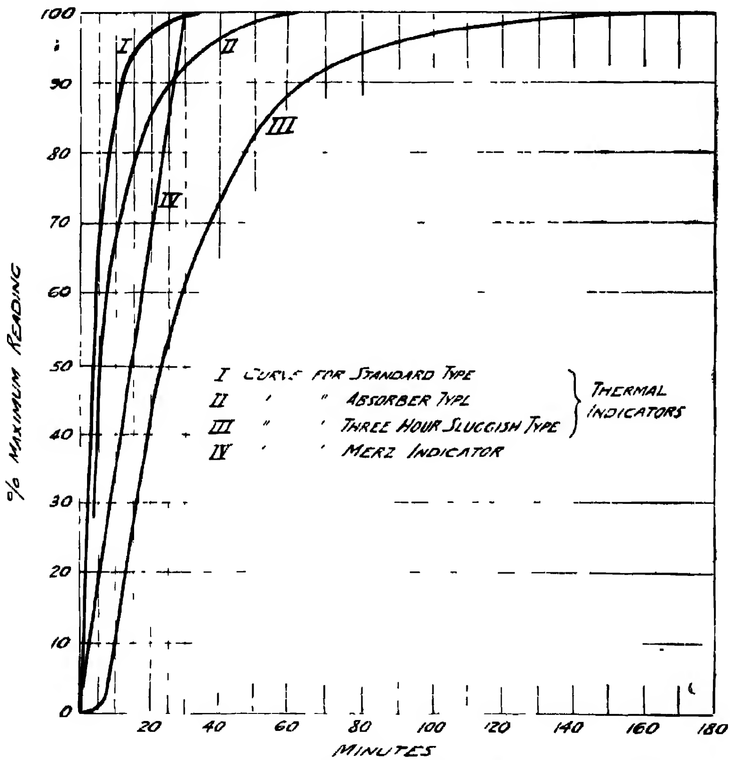


FIG. 124. Curves showing time lag of different types of demand indicator.

of reactive kVA. Figs. 126–128 show the metering errors which have to be allowed for. Care is necessary in the choice of positions for metering equipments and the following points require special attention : freédom from vibration or damage, minimum of obstruction or inconvenience ; absence of moisture or fumes ; access and light for reading ; freedom from interference ; vertical position for the meters.

The mounting of meters on a separate panel, which can be either of the wall-mounted or self-supporting type, is now the general practice for many of the consumers and general supply sub-stations. Figs. 129–131 show some typical installations. Meters should never be fixed

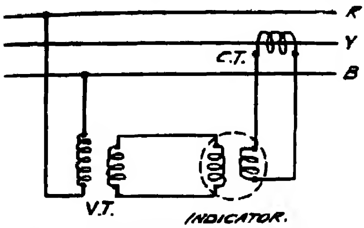


FIG. 125. Reactive kVA indicator.

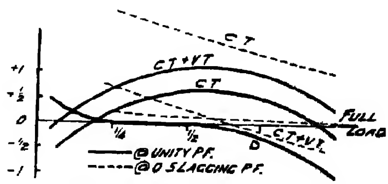


FIG. 126. Meter error curves under differing conditions.

near large masses of metal or heavy current carrying cables. They should always be connected with the current and voltage transformers with which they have been tested and where additional apparatus is used on the same transformers such additional apparatus should be

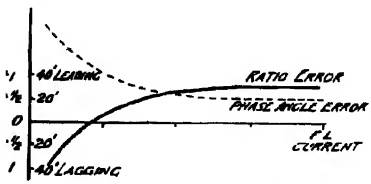


FIG. 127. Current transformer error curves.

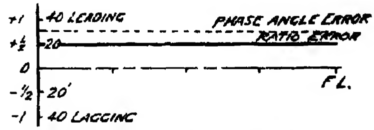


FIG. 128. Voltage transformer error curves.

connected in circuit when the meters are tested. Where current and voltage transformers are used, one side of each secondary winding should be earthed and in all cases a separate lead should be run to the meters from the earthed point of the secondaries of these transformers. Earth connections should not, under normal operation, carry current. Meters should be sealed before they are issued for service and these seals should not be broken except in special circumstances. Meter terminal covers, demand indicators, transformer secondary terminal covers, M.V. voltage transformer fuses, test links and any other point where interference is possible, should be sealed. The current coils of current transformers in the case of polyphase meters, having two current coils, are inserted in the red and blue phases, and the corresponding voltage coils are red-white and blue-white respectively. The rotation of phases on this particular system is blue-white-red,

so that on the two-wattmeter method the red phase meter gives the higher reading with lagging power factor load and the lower reading with leading power factor load.

FIG. 129 Wall-mounted metering panel.

Batteries and Charging Equipments. Where manual or spring-closing is in use, a small tripping battery (Figs 132 and 133) will suffice. In outlying districts A C tripping may be relied upon, either direct or by way of a relay. Trickle charging equipment by which a battery already in a fully-charged condition may be maintained indefinitely in that state, without the need for periodical charges and discharges, is frequently employed A very small current—just sufficient to balance the losses which occur on open circuit—is passed through the battery continuously Insufficient charge is responsible for rapid deterioration of the plates It is also claimed that a battery with trickle charge equipment may be placed in a room where metalwork is unprotected, for there is no gas given off, and no corrosion With an A C supply a rectifier is necessary, but if D.C. is at hand, then resistances will serve to regulate the current

The batteries should be placed near the control circuits, and preferably in close proximity to the control room Where batteries of large capacity are installed they should, wherever possible, be housed at

ground level to facilitate handling. The room should be of sufficient size to permit of easy access for inspection and maintenance of every cell. A concrete floor will be quite satisfactory provided the necessary care is taken to keep it acid free. The concrete may be covered with a layer of acid-resisting asphalt (Fig. 134); treated with silicate of soda; or coating of wax which prevents wear and consequent dust trouble. To minimise corrosion it may be necessary to treat all wood and steelwork with acid-proof paint and enamel. Copper conductors and connections may also require such treatment. Evaporation is prevented by covering the acid level of each cell with a thin film of oil. A water supply, with sink, bench, etc., should be installed for flushing, cleaning, and overhaul. The connections between the various sections of the battery and switchboard are of bare copper rod or strip, maintained rigid and at least 8 ft. high to prevent accidental contact. Motor generators are rarely used for charging as the metal rectifier has many advantages. The charging equipments—whether motor generator or rectifier—are placed in a room adjoining or immediately above the battery room providing the ingress of acid fumes is prevented.

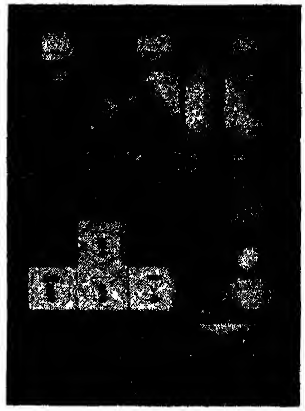


FIG. 130. Metering panel (self-supporting).
Secondary wiring in steel channel.
M.V. Supplies:
Day and night units on 3–3 phase 4 wire meters. Total kVA demand summated on Trivector which also gives a check on the total units.

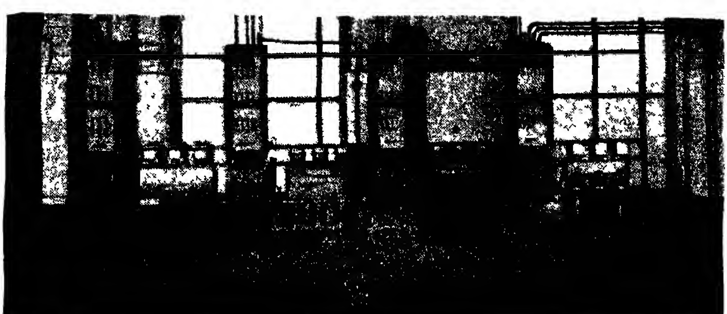


FIG. 131. Works metering equipment.

The switchboard can be accommodated in the charging equipment room and arranged for connection to the end regulating cells. The switchboard is of the flat-back type, and should be screened to prevent unauthorised access at the back. Small tripping batteries are wall-mounted in a wood cabinet. Fig. 135 shows the main connections of a

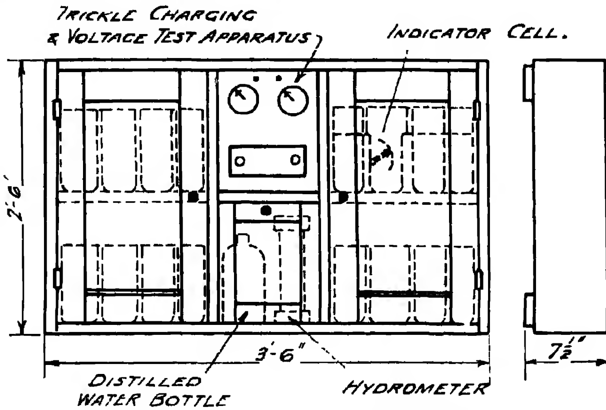


FIG. 132. Small battery trickle charging equipment.

typical equipment which provides for : Trickle Charge, Quick Charge, Charge and " Off ". The value of the resistance is such that a fully-charged battery will pass a test current equal to one half the rated capacity of the battery. The use of an ammeter is preferable to a voltmeter, as it ensures that a test current is definitely passing. The ammeter is marked to show fully charged and discharged conditions. The battery is of the nickel-cadmium alkaline type, and Table 13 gives typical details :

TABLE 13. *Battery Data*

A.H. capacity, 10-hour rate	Charge		For circuit breaker tripping currents up to amps.
	Trickle mA.	Quick amps.	
5	17	0·2	15
10	33	0·2	30
15	50	0·3	45
25	83	0·5	75

Lead acid and alkaline cells should not be housed in the same room.

Typical equipment particulars are given for a 33/6·6 kV Sub-station—Battery Equipment.

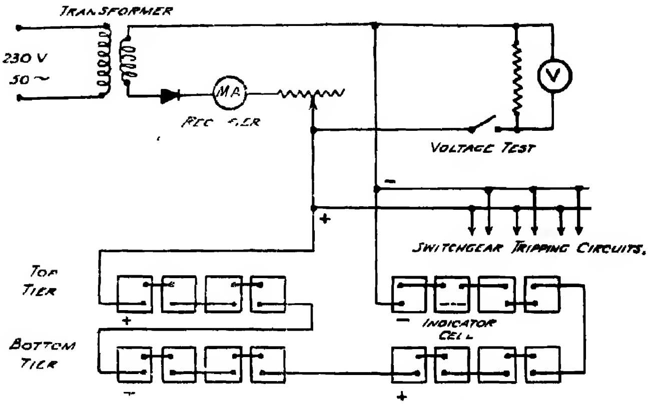


FIG. 133. Small tripping battery with trickle charging equipment.

The sub-station (Fig. 136) contains five 33 kV, 750 M.V.A. and two 6·6 kV, 250 M.V.A. O.C.B.'s, which have remote electrical operation for closing and tripping, and emergency and pilot lighting are provided. One battery is installed having a nominal voltage of 110 volts and an output of 450 amp. hours when discharged in ten hours, with a final voltage of 1·85 volts per cell. A mains transformer, ratio 230/110 volts, to give 15 amps. continuously on the secondary side is included for normal lighting services. In the event of failure of this supply, the lighting circuits are automatically connected to the battery by a

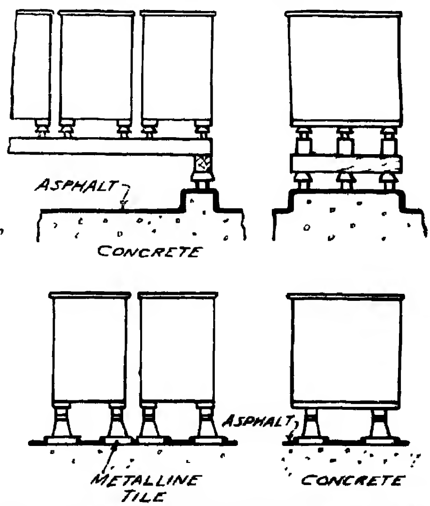


FIG. 134. Methods of supporting heavy cells.

contactor. When A.C. supply is re-established the contactor returns automatically to its original position, thus placing the battery on trickle charge. Contacts are included for disconnecting the charging circuit and for operating an alarm when the battery is discharging on load. A testing push-button is also provided. One metal oxide rectifier, having an output of 500 mA. at 125/140 volts, is installed for trickle charging. A motor generator, Fig. 137, re-charges the battery after complete discharge in eight and half hours.

Battery.

Discharge :

45 amps. for 10 hours	. .	Final volts 1·85 per cell.
75 ,, ,, 5 ,,	. .	,, ,, 1·82 ,, ,,
225 ,, ,, 1 ,,	. .	,, ,, 1·75 ,, ,,
297 ,, ,, ½ hour	. .	,, ,, 1·69 ,, ,,
639 ,, ,, 1 minute	.	,, ,, 1·60 ,, ,,

Charge :

Normal—any convenient rate up to 62 amps.
Maximum—125 amps.

Efficiency :

Ampere-hour	90 per cent
Watt-hour at 10-hour discharge rate . .	75 ,, ,,
,, ,, ,, 5-hour ,, ,, . .	73 ,, ,,
,, ,, ,, 1-hour ,, ,, . .	68 ,, ,,

at normal charging rate.

Dimensions of plates :

Positive—7 in. wide, 9¾ in. 12 mm. thick.
Negative— ,, ,, ,, 8 ,, ,,

Motor generator :

70 amps. at 116/135 volts.
31 ,, ,, 116/160 ,,

Safetylyte equipment is installed.

Nickel-cadmium storage batteries are also in use. They have a long life, require a minimum of attention and checking, do not require monthly overcharging which facilitates operation of the supervisory control system and require less space for a given capacity. Maintenance requirements during the first year are broadly as follows : voltage

reading once per month ; specific gravity test once per six months and later once a year ; electrolyte level check once every three months and six months later ; cleaning of cells, connections and racks once a year

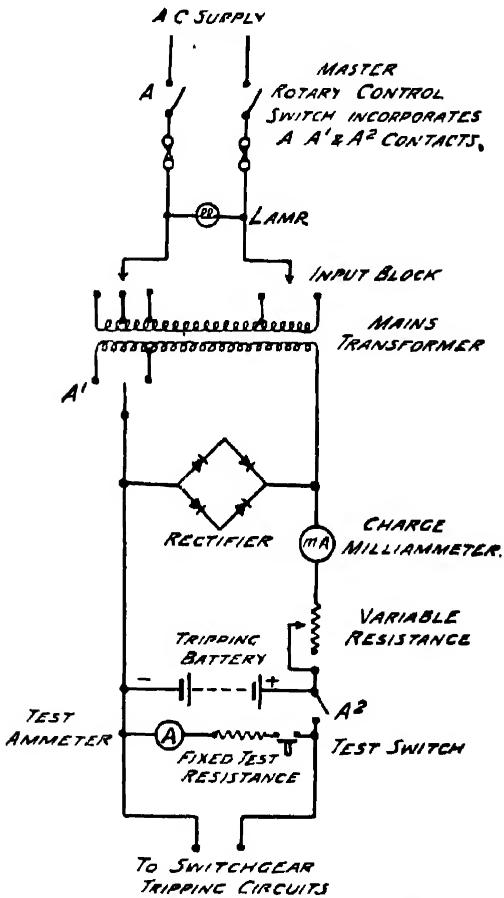


FIG. 135. 30-volt tripping battery with charging equipment.

and once every two years later. A life of twenty-five years and over is quite usual. Since this type of cell can be stored fully charged for long periods without apparent damage, due to the low self discharge and lack of sulphation of the negative plate, it has the added advantage of

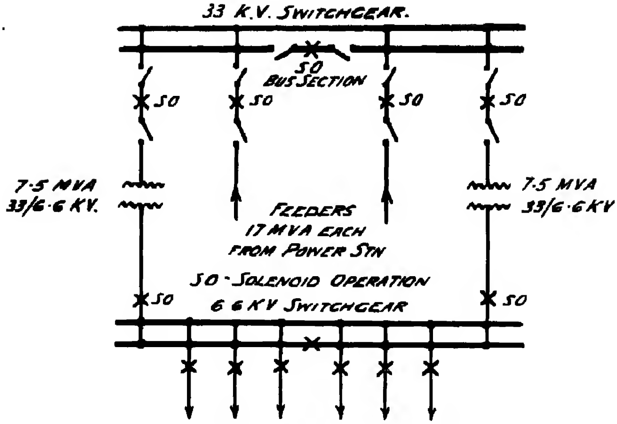


FIG. 136. Key diagram of sub-station.

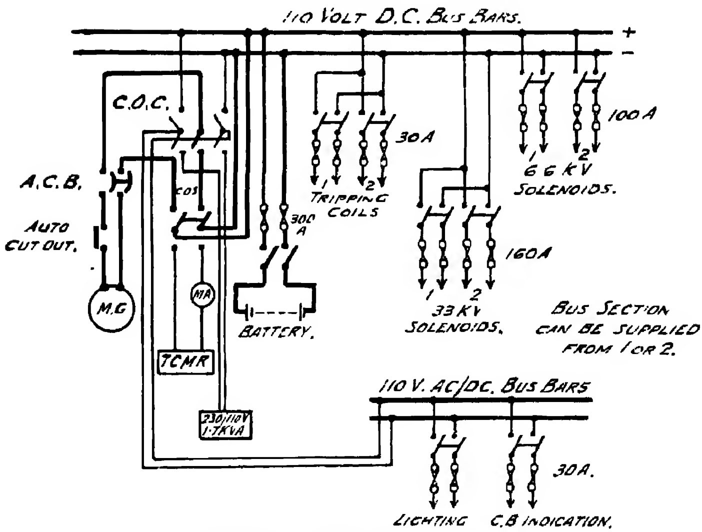


FIG. 137. Diagram of connections for battery equipment.

not requiring attention when unavoidable delay is experienced in the construction of a new sub-station.

Earth Fault Indicators. Earth fault indicating lamps, together with two voltmeters, may be included. If lamps are used they may pass sufficient current to operate sensitive relays (alarms, etc.) and so pro-

duce an earthed system. A sensitive earth leakage alarm may be arranged to give warning should the insulation resistance fall to, say, 20,000 ohms. Some control board relays operate at 10 mA, and with a single earth fault a relay has operated by the leakage current of the earth detector. To retain the advantages of continuous leakage detection of an insulated system, a minimum current for any relay is specified at 50 mA.

Technical Data. The allowable current densities for different sections of equipment are :

Contact surfaces (bolted) . . .	125 amps. per in.^{2}
,, ,, (tinned and bolted) .	200 ,, ,, ,,
Busbars (indoor and enclosed) . .	750 ,, ,, ,,
,, (outdoor)	1,200 ,, ,, ,,
Isolating switches, etc. . . .	50–100 ,, ,, ,,

Expansion of busbars may be estimated from the usual formulae :
$L_2 = L_1 (1 + \alpha T)$
Where L_1 — original length, in.
L_2 — new length, in.
T — temperature rise °C.
α — coefficient of expansion (0·0000166 per °C. for copper).
Busbar forces may be estimated from B.S.S. 159—1932.
(*a*) Allowing for resonance (Fig. 138)

$$F = \frac{5.\ 4 \cdot 5.\ L.\ I_s^2}{r} \cdot 10^{-8}$$

Where 5 — resonance factor.
I_s — initial R.M.S. value of the symmetrical component of the S.C. current.
L — length of conductor under consideration, in.
r — spacing of centres of conductors, in.
F — maximum instantaneous force, lb.

(*b*) Neglecting resonance

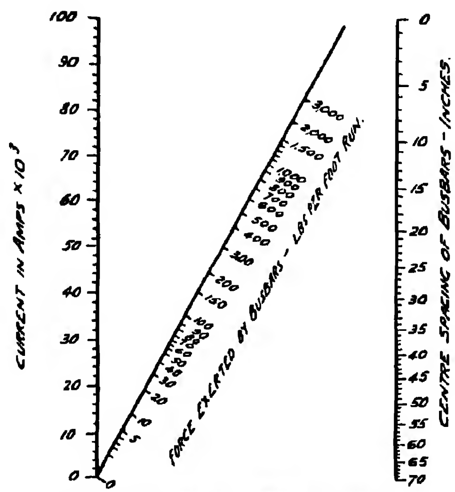
$$F = \frac{4 \cdot 5.\ L.\ I_a^2}{r} \cdot 10^{-8}$$

The main object of the isolation of phases is to prevent the possibility of a dead short circuit between phases as the currents which flow

are large, and the possible explosive and destructive effects very great. Where I_a^2 is the initial R.M.S. value of the asymmetrical current.

$$\text{Since } I_a = \sqrt{3}.\ I_s$$

$$F = \frac{4{\cdot}5.\ L.\ 3.\ I_s^2}{r} \cdot 10^{-8}$$



THE ABOVE NOMOGRAM IS COMPUTED FROM THE FORMULA: $F = \frac{5.4 I^2 10^{-7} K}{S}$

WHERE F = FORCE IN LBS PER FOOT RUN, S = SPACING IN INCHES.

$I = \text{CURRENT IN AMPS} = \frac{\text{SHORT CIRCUIT KVA} \times 1000}{\text{LINE VOLTAGE} \times \sqrt{3}}$

K = RESONANCE FACTOR = 5.

TO ESTIMATE THE FORCE EXERTED ON BUSBAR DURING SHORT-CIRCUIT CONDITIONS PLACE A STRAIGHT EDGE ON THE VALUE OF AMPERES INVOLVED IN THE SHORT CIRCUIT AND ON THE CENTRE SPACING OF THE BUSBARS THE INTERSECTION OF THE STRAIGHT EDGE WITH THE FORCE.
FORCE LINE GIVES THE FORCE PER FOOT RUN.

FIG. 138. Busbar short-circuit stress nomogram.

The minimum cross-section of copper conductor required to meet thermal consideration may be estimated as follows :

$$I = 13A.\ \sqrt{T/t}$$

Where I — R.M.S. value of the short-circuit current in amps. for the duration it flows.

A — sectional area of conductor, mm.^{2}
T — admissible temperature rise, °C. (150° C.).
t — duration of short circuit, secs.

Assuming $t = 1$ second, the safe current density is about 100,000 amps. per in.^{2}

A figure of 120,000 amps. per in.^{2} is a figure often adopted for the maximum permissible current density (breaking).

The electrical clearances recommended for indoor and outdoor working are given in B.S.S. 162.

Circular conductors are not ideal for current carrying since A.C.

TABLE. 14. 6·6 *kV*, 250 *M.V.A. Metal-clad Ring Main Switchgear Costs* (1945).

Maker	Ring main unit and O C B £	Metering equipment £	Spring-closing mechanism £	Erection £	Tools, etc £	Total cost (excluding oil) £
(1)	756	147	(included)	56	23	982
(2)	702	154	44	55	25	980
(3)	685	150	43	54	24	956
(4)	554	92	45	20	5	716
(5)	420	70	32	15	11	548
(6)	336	77	40	24	4	481

does not penetrate into the body of the conductor to a greater depth than :

$\frac{3}{8}$ in. at 50 cycles per second.
$\frac{1}{2}$ " " 25 " " "

Costs. Some idea of switchgear costs will be observed from Table 14. Figs. 139 and 140 indicate the comparative costs for different rupturing capacities.

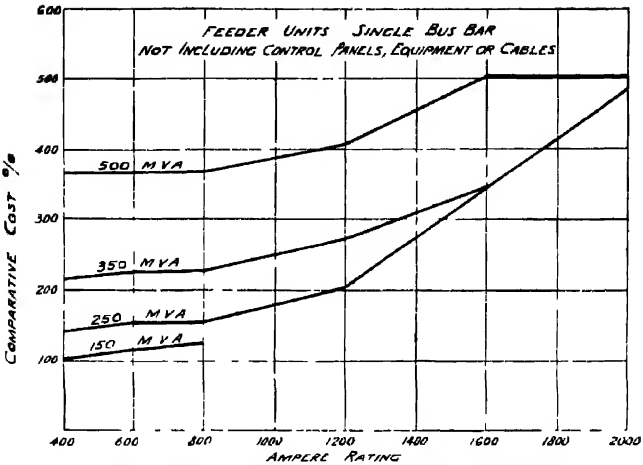


FIG. 139. Comparative cost of 6·6 kV switchgear.

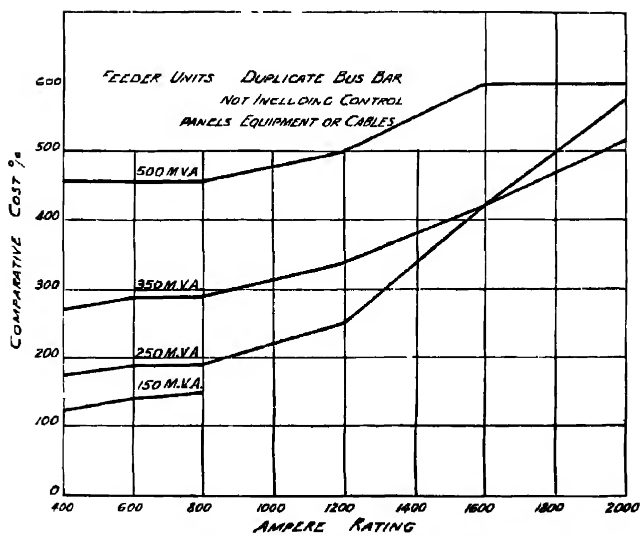


FIG. 140. Comparative cost of 6·6 kV switchgear.

Bibliography

A. ARNOLD. "Switchgear Practice." (Chapman & Hall.)
T. H. CARR. "A Switchgear Failure," *Electrical Industries*, October, 1945.
,, "Electricity Sub-stations," Draughtsman Publishing Co., 1945.
,, "Electric Power Stations," Vol. 2. (Chapman & Hall.)
J. CHRISTIE. "Air Blast Switchgear and its Application," *Electrical Power Engineer*, April, 1946.
W. A. COATES. "Small Conductors on Busbars of Large Systems," *Metropolitan-Vickers' Gazette*, June, 1920.
W. A. COATES and H. PEARCE. "*Switchgear Handbook.*" (Pitman.)
H. E. COX and L. DRACQUER. "Oil-less Metal-clad Switchgear for Medium A.C. Circuits up to 660 volts, Three-phase," *Journal I.E.E.*, Vol. 87, 1940.
H. E. COX and T. W. WILCOX. "The Influence of Resistance Switching on the Design of High-voltage Air Blast Circuit-Breakers," *Journal I.E.E.*, Vol 91, 1944.
H. W. CLOTHIER, B. H. LEESON and H. LEYBURN. "Safeguards against Interruption of Supply," *Journal I.E.E.*, Vol. 82, 1938.
K. DANNENBERG and W. J. JOHN. "A High-voltage High Rupturing Capacity Cartridge Fuse and its Effect on Protection Technique," *Journal I.E.E.*, Vol. 89, 1942.
D. R. DAVIES and C. H. FLURSCHEIM. "The Development of the Single Break O.C.B. for Metal-clad Switchgear," *Journal I.E.E.*, Vol. 79, 1936.
J. W. GIBSON. "The High Rupturing Capacity Fuse, with special reference to Short-Circuit Performance," *Journal I.E.E.*, Vol. 88, 1941.
J. A. HARLE and R. W. WILD. "Restricting Voltage as a Factor in the Performance, Rating and Selection of Circuit-Breakers," *Journal I.E.E.*, Vol. 91, 1944.
A. P. HARVEY. "Design and Testing of Circuit Breakers with Reference to Collieries," *Mining, Electrical and Mechanical Engineer*, July, 1944.
J. HENDERSON. "Grid Metering," *Journal I.E.E.*, Vol. 75, 1934.
M. C. HUNTER. "Mechanical Integrity in the Design of Electrical Circuit-Breakers," *Journal I.E.E.*, Vol. 87, 1940.
R. T. LYTHALL. "Switchgear Handbook." (Johnson & Phillips.)
E. C. McKINNON. "Storage Batteries—A Review of their Application," *Journal I.E.E.*, Vol. 87, 1940.
J. H. C. PETERS. "Air-break and Air-blast Switchgear," *Mining, Electrical and Mechanical Engineer*, March, 1946.
E. I. PILCHER. "Short-Circuit Forces on Busbars and Connections in Cellular Switchgear Construction," *World Power*, 1935.
R. W. TODD and W. H. THOMPSON. "Outdoor Switchgear." (Pitman.)
R. TEARSE. "Sub-station Switchgear," *Electrical Times*, 2nd January, 1947.
H. TRENCHMAN and K. J. R. WILKINSON. "Restricting Voltage and its Import in Circuit-breaker Operation," *Journal I.E.E.*, Vol. 80, 1937.

CHAPTER VI

TRANSFORMERS, REACTORS AND REGULATORS

TRANSFORMERS

The transformer, which may be of the core or shell type (Fig. 141) is enclosed in a steel tank and immersed in oil the tank being fitted with circulating tubes or radiating fins through which the oil circulates naturally, thereby increasing the cooling surface. With oil-immersed forced-cooled transformers, the cooling medium may be either air or water, external cooling being preferred in this country. The cooling equipment comprises: oil cooler of the radiator type for air cooling; circulating oil pump and air blowers, together with circulating water pump if sufficient static head and water quantity are not available. More floor space is required for radiator and air blast methods than with water cooling. The need for auxiliaries and periodic attention, together with risks involved should the cooling plant fail, has

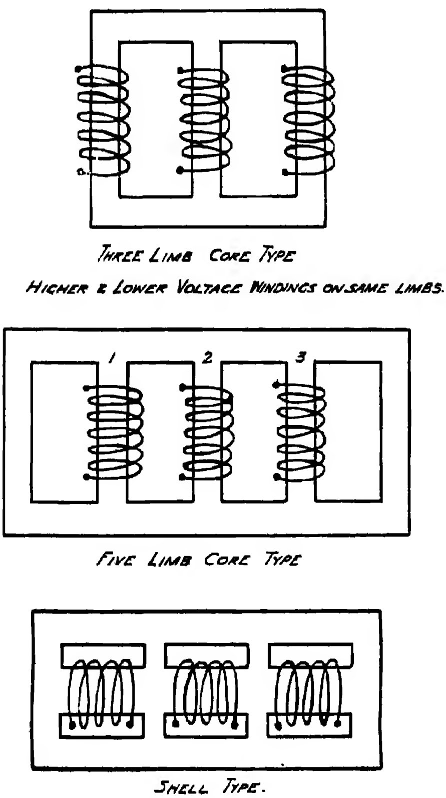


Fig. 141. Transformer types.

encouraged the use of self-cooled transformers in the larger capacities, although the cost is greater than corresponding forced-cooled units.

The forced oil natural cooling (O.F.N.) is useful where for reasons of space the radiating surface has to be some distance from the transformer. The oil is pumped round the cooling system, from which radiation is by natural air.

The rate of rise of temperature of an oil-immersed transformer is much less than an air insulated one and is therefore able to withstand short-time overloads. The high heat capacity of the oil makes it suitable for removing heat from hot spots in the transformer to the external cooling surface. The relatively low breakdown strength of air necessitates large clearances thereby increasing the overall size. The oil adds considerably to the impulse strength of the unit, but periodic testing and cleaning, greater weight and fire risk are disadvantages.

	Oil	Air
Density-grams/cc	0·87	0·0013
Specific heat	0·48	0·24
Thermal Conductivity :		
MW/CM/CM^2/°C.	1·60	0·25
Breakdown strength rms.kv/cm. .	100/120	21
Liable to deterioration . . .	Yes	No
Inflammability	Yes	No

TABLE 15. *Methods of Transformer Cooling*

Method of cooling	Type	Abbreviation
Natural cooling	Oil-immersed natural cooling . . .	O.N.
Artificial air cooling. (With air blast.)	(*a*) Oil-immersed air blast cooling . . .	O.B.
	(*b*) Oil-immersed forced-oil circulation with separate oil cooler and air blast cooling.	O.F.B.
Partial artificial cooling.	(*a*) Oil-immersed natural cooling for a predetermined output with air blast.	O.N./O.B.
	(*b*) Oil-immersed natural cooling for a predetermined output, with forced-oil circulation with separate oil cooler and air blast cooling above this output.	O.N./O.F.B.
Artificial cooling (With water circulation.)	(*a*) Oil-immersed water cooling . . .	O.W.
	(*b*) Oil-immersed forced-oil circulation with separate oil cooler and water cooling.	O.F.W.
Natural cooling (Part)	(*a*) Oil-immersed forced oil circulation . .	O.F.N.

Conservators are fitted on (Fig. 142) many outdoor transformers, and some engineers have standardised throughout, whether for outdoor or indoor service. Not only does this reduce spares, but in view of the deterioration of transformer oil it appears justifiable to fit conservators. The tank and fittings must be oil-tight, and the transformer is therefore weather-proof.

Transformers may be fitted with skids instead of the more usual wheels or rollers. With many sub-station sites handling on timbers and tubular rollers is easier and safer. Adequate jacking facilities should be specified to suit the construction jacks in use. Transformers can be fitted with valves (standard 2-in. gas-threaded) for connection

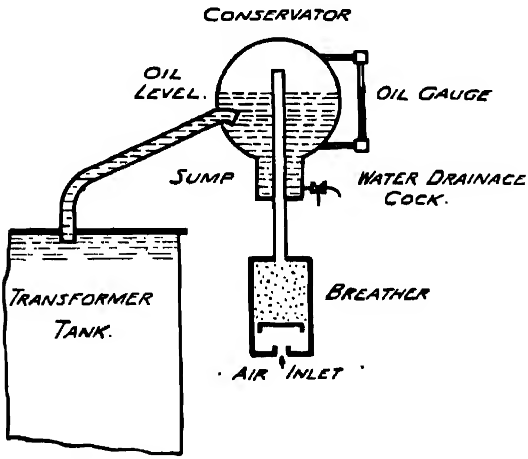


FIG. 142. Transformer oil conservator.

to oil pipes for purification purposes. Each detachable radiator may be fitted with top and bottom valves and these prove useful at times. Thermometer pockets are usually provided on all power transformers and on outdoor oil-filled current and voltage transformers for E.H.V.

To allow for the expansion of oil under working conditions, a transformer must breathe, and it is inevitable that some moisture will be drawn into the air space above the oil. This ultimately condenses on the underside of the tank cover and may fall through the oil to the windings, eventually causing failure. The surface area of the oil exposed to the atmosphere is reduced, whilst the surface temperature of the oil in the conservator is reduced. The air space above the oil may also be filled with volatile gases, thus forming an explosive mixture.

Ignition of the gases has taken place, and resulted in serious damage to transformers and buildings. The inclusion of a conservator enables Buchholz protection to be fitted, any gases given off from the oil pass to the conservator *via* the protective relay causing an indication to be given of their presence. The extra cost of the conservator is small compared with the total cost that is justifiable on the smallest transformers.

Transformers are designed for operation with their higher and lower voltage windings each connected to an electrical system, the neutral of which is earthed, either direct or through a resistance or reactance, or a combination of both at one or more points. The harmonic voltages are suppressed to eliminate the possibility of high frequency disturbances, inductive effects, or circulating currents between the neutral points of inter-connected systems, reaching such a magnitude as to cause interference with post office or other communication circuits. Where the higher and lower voltage windings of a transformer are connected star-star, a delta connected tertiary winding is provided for that purpose. Tertiary windings may also be included for supplying a different voltage (Fig. 143). For this duty the winding may be connected in star or delta, its rating being determined by load requirements. If the tertiary winding is delta connected and the load is small, other factors referred to later have to be allowed for. This winding may also be used to supply synchronous or static condensers for improving the voltage regulation and power factor of a transmission system when the primary and secondary voltages are unsuitable. The effect of saturation of the iron circuit is to introduce a third harmonic into the phase-voltage wave, but this does not affect the wave form of the line voltage. The third harmonics in the phases of a star-connected system cancel each other as far as the line voltage is concerned. In the tertiary delta winding the three induced e.m.f.'s assist each other in setting up a third-harmonic circulating current which opposes the introduction of the third-harmonic current into the phase voltage. This trouble appears in both the shell and core types of three-phase star-star transformers, but the problem is not nearly so great in the core type due to the better construction of the three cores. If the winding had only to cater for the circulating current the kVA rating would be small, but if a short circuit should take place between one line and neutral on the primary side, the current would be limited only by the reactance between the primary and tertiary windings. The current then flowing in the tertiary winding would be sufficient to

balance the ampere-turns in each phase caused by the short-circuit current. The rating of this winding should be such that it will not suffer damage in the event of a fault on either the primary or secondary sides. Much therefore depends on the protection included and the reactance of the electrical system. A minimum of 25 per cent. of the main transformer kVA rating is usual, but local conditions have to be taken into consideration. One supply authority specifies a rating of $33\frac{1}{3}$ per cent. capacity. On some of the earlier transformers trouble was experienced under fault conditions due to displacement of the tertiary as the result of inadequate capacity and bracing. To limit the current in the tertiary, external reactors were inserted in the delta connection and no tertiary failures were subsequently experienced. It

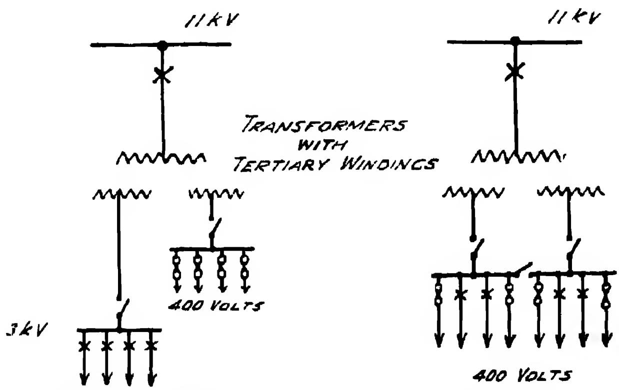


FIG. 143. Supplies from tertiary wound transformers.

may be argued that specifying a rating without reference to the reactances of the main windings is no criterion of the strength of the tertiary winding under fault conditions. It would appear that if it is specified that the transformer shall be suitable for given short-circuit conditions it is unnecessary to specify the size of the tertiary winding. A tertiary winding may also be used to permit of unbalanced loading on the secondary side between the lines and neutral of a star-star transformer. Any out-of-balance current, by causing a slight variation of the phase voltages, sets up a current circulating round this winding, and, by transformer action, allows the out-of-balance current to flow through the remaining phases of the primary winding.

The flux density in any part of transformer cores is generally kept within 11,000 and 14,000 at normal ratio. A reduction in flux density

reduces noise but entails additional cost, the latter, however, being partly offset by the reduction in iron loss accruing. The iron loss can be reduced by increasing the cross-sectional area of the core, or by increasing the number of turns. The former method results in an increased length of mean turn, and hence the copper losses, whilst the latter method also increases the resistance of the windings. High flux densities also result in increased magnetising current and higher harmonics in the wave form of the primary current, secondary voltage, or both. Harmonics in the secondary voltage may affect the operation of static condensers used for power factor correction, and also cause sparking on rotary converting plant. The additional current also impairs voltage regulation and loads up the distribution cables. The majority of transformers for sub-station service are fitted with an off-load voltage tapping switch, so that voltage control can be effected as district loadings vary. Core bolt insulation has been known to fail, thus causing eddy currents in the bolt resulting in overheating and in one case a bolt was almost fused to the core and carbonised. The bolts clamping the laminations together may be wrapped with leatheroid to insulate them from the core laminations and are carefully insulated from the clamping plates. One vertical row of bolts is used even on large cores. The use of two or more rows holds a prospect of trouble resulting from circulating currents in the bolts due to damage or displaced insulation. For larger transformers it is usual to include remote electrically-operated on-load voltage control or tap-changing equipments.

Transformer tanks should be designed to prevent the collection of moisture on any part, and where troughs and cavities exist drainage should be included. A relief valve is provided in the top cover of indoor types to release any gas under pressure which may collect in the tank. Many units have a relief outlet fitted with a diaphragm of mica, bakelite, glass or copper foil which affords protection against tank failures due to explosion. Should a Buchholz relay be required, the relief outlet or explosion vent has two diaphragms, one at the bottom of the escape pipe and the other at the top. In this way, any gases produced inside the tank must pass through the relay instead of being released to the relief vent. If the bottom diaphragm is punctured, the oil rises in the escape pipe and is clearly seen in the sight indicator. Where a conservator is provided, a breather should be fitted to ensure that moisture is not admitted to the transformer when breathing takes place. The oil connection between the conservator

and transformer tank should stand at least 1 in. high inside the vessel, so that any water which condenses in the conservator is prevented from entering the tank. A small drain enables this trap to be emptied. Chloride crystals were used in the earlier breather designs, but silica gel is now the most favoured drying agent. In silica gel breathers indications of moisture are given by the changing of the coloured crystals from blue to pink. The gel may be reactivated by removal from the breather and heating to 150°–200° C. for two or three hours, or until such time as the original blue colour reappears. Some engineers have installed transformers without conservators or breathers and apparently they have proved quite satisfactory.

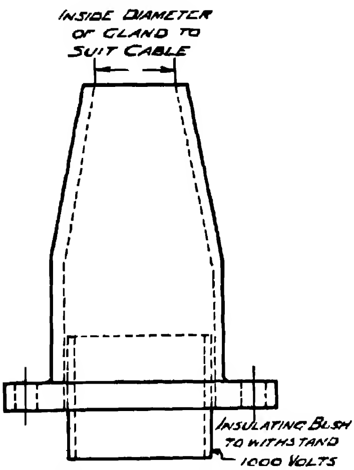


FIG. 144. Transformer cable gland.

Cable box design for transformers and reactors is worthy of attention if trouble-free working is to be obtained. The boxes should be of adequate proportions to enable a large compound area to be maintained under all working conditions. Shrinkage takes place due to compound—over a period of time—draining into the cable. It is more pronounced on transformer and reactor cable boxes than switchgear, due to the higher conductor temperatures. This temperature variation results in greater expansion and contraction, and in the process of contraction compound is drawn from the cable box into the cable. During subsequent expansion the compound is not pushed back into the box, but remains and swells the lead on the cable. A styrene " plug " may be included which produces a barrier joint effect as far as migration of compound is concerned, without introducing actual joints. An example is the inclusion of a styrene plug in the end of a tail cable from a transformer. This enables the transformer cable boxes to be filled with oil, working under the conservator system, and eliminates—due to compound expansion and contraction—leakage, etc. On pole type transformers the bushings can be set at an angle to enable their inner terminations to be below oil level in order to ensure that any flashover due to lightning takes place outside and not inside. This is

the result of failures on early transformers which were fitted with short-shank insulators terminating above oil level. An alternative to cable boxes is brass glands (Figs. 144 and 145) for both the higher and lower voltage sides, which enables the cables to be taken direct into the tank and wiped direct on to the glands. The glands can be arranged for cables to be taken out at any angle desired. Should the cables be run underground, it is possible to loop the higher and lower voltage cables overhead in such a manner that syphoning of oil into cables is eliminated. Non-bleeding cables are used with such glands, and all glands are insulated from the tanks to withstand a test voltage of 1,000 volts or above. Terminating pre-impregnated paper cable directly into the tank eliminates an extra chamber or box, but a transformer failure may damage the cables. This method is suitable for larger transformers provided the cable tails are sealed with silk tape. It is an advantage for each cable box to be connected to the windings through an oil-immersed flexible disconnecting link, which is mounted in a separate compartment. In this way a transformer can be removed without interfering with the boxes and fixed cabling. Cable boxes are filled with either compound or oil, the latter being favoured for higher voltages. Unless the joints are perfectly made and maintained in good order, considerable trouble may result from continued leakage. This also applies to auxiliary boxes and tanks fixed to the transformer, and usually results in the cable compound mixing with oil in the tanks. Oil-proof compound has been used and appears to give satisfaction. The joints of cable boxes should be maintained in good order, otherwise

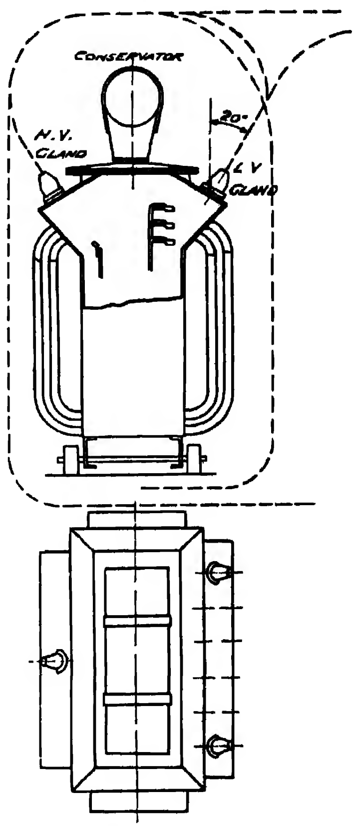


FIG. 145. Transformer cable arrangement.

ingress of moisture will result in cable failure. Breathing is always taking place *via* joints, and after being in service for some time, particularly in a humid atmosphere, moisture may find its way into the cable boxes. Fabricated steel boxes are susceptible to such troubles, and hard rubber gaskets are not suitable for cover joints. Cork composition with a jointing mixture appears to be satisfactory. Hard rubber washers, however, appear to be suitable for screwed plugs. Where joints have to be periodically broken, it has been found that by using a fixing paste on the permanent side and vaseline on the removable side, joints can be broken without damage to the gaskets. Indoor

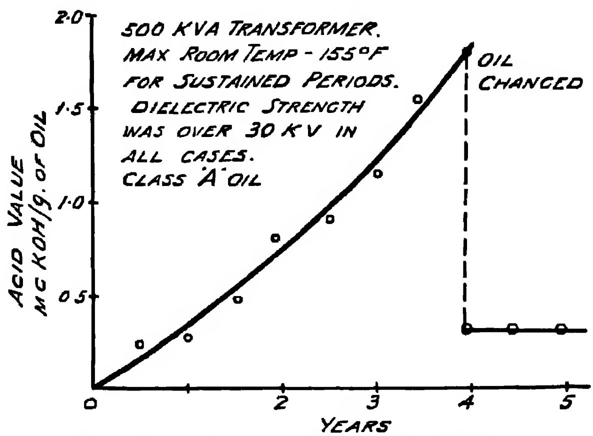


FIG. 146. Growth of acidity in transformer oil.

transformers may be fitted with porcelain bushings arranged for bare H.V. and M.V. connections, which enable a unit to be changed without the necessity for cable jointing and its increased time. Outdoor units can also be provided with special cable-termination arrangements to expedite change of units. One method is to use single-core cambric insulated lead-covered cables (11 kV) which are plumbed off to a standard brass gland which is clamped to the tank. A universal indoor or outdoor unit is practicable by using a detachable gland or insulator.

Oil for transformers may be either A30 or B30, in accordance with B.S.S. 148. Both have been found satisfactory, but B30 has been generally favoured since it is contended A30 oil has contributed towards breakdowns due to increase in acidity. Class B oil is cheaper and has given satisfactory service. Prolonged overloading at high temperatures

causes deterioration of the oil, and one effect is the formation of acid (Fig. 146). A theory is that the oil tends to oxidise through being further aggravated by the presence of metallic copper which acts as a catalyst. Volatile acids condense on the underside of the tank cover, and in time result in corrosion. Oxidation of the oil is reduced if a conservator is fitted, and the volatile acids are prevented from condensing on the tank cover. Opinions differ as to the figure at which it is safe to continue with oil of a known acid content, but a value of 1 to 2·5 m.g. KOH

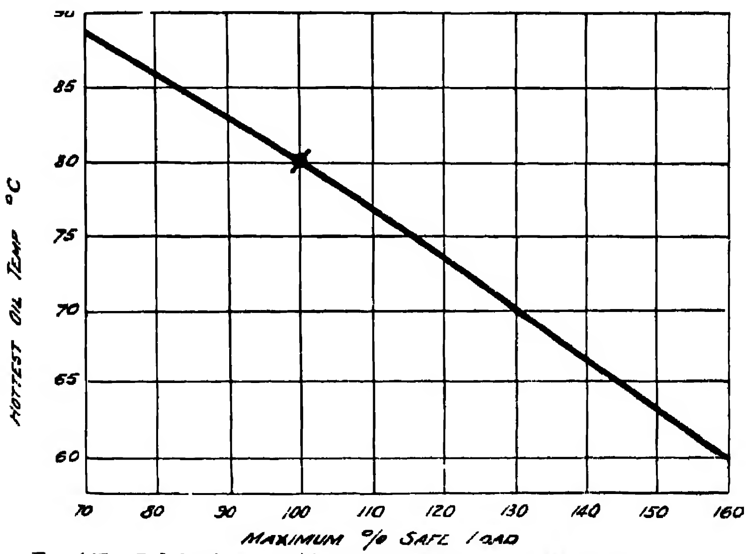


FIG. 147. Safe loading conditions for typical oil-immersed natural-cooled transformer.

per gramme of oil has been suggested as a maximum. British Electrical and Allied Industries Research Report No. E/T54 makes certain recommendations concerning transformer oil. Failure of core bolt insulation may result in intermittent sparking, impairing the characteristics of the oil and forming explosive gases. Gas pressure will be set up and accumulated if the oil is decomposed by arc or heat from the following: (1) poor contacts, (2) flashover or creepage; (3) puncture of insulation; (4) corona; (5) turn to turn short circuits; (6) poor oil circulation or level. Care should be exercised when opening up, or working on transformers, where trouble has been experienced or where the oil is found to have deteriorated. The formation of sludge in

transformer oils is not yet fully understood, but it would appear that it results from sustained high temperatures with consequent oxidation of the oil. Sludge adversely affects operation by clogging the cooling ducts, lowering the flash point and increasing the viscosity of the oil, thus reducing transference of heat from the windings. To minimise the danger of fire risk, the oil should have a high flash point, and 290° F. has been suggested as a minimum. The presence of impurities or moisture may considerably reduce the dielectric strength. It will be noted from Fig. 149 that there is no single critical value of hottest oil temperature. It gives the maximum oil temperatures for various loadings, and if the load is 100 per cent. the oil temperature must not exceed 80° C., but whether the transformer can carry this load continuously depends upon the surrounding air temperature. This curve may be applied to temporary as well as to continuous loadings. An overload of 40 per cent. may be applied until such a time as the oil temperature attains a value of about 67° C., and this is true no matter what the previous loading conditions were. The curve shows the possible danger of using hottest oil temperature as a protection or alarm device. If the oil thermometer were set to operate the alarm when the hottest oil temperature exceeded 80° C., the curve shows that the alarm would be given quite unnecessarily so long as the load was below 100 per cent. On the other hand, the transformer may be carrying a load exceeding 100 per cent. and greater than the maximum safe limit without the alarm operating. Figs. 148 and 149 illustrate winding temperature indicators and Fig. 150 oil purifying plant. Transformers are sometimes shipped without oil, but have the tanks filled with CO_2 to prevent the entry of moisture.

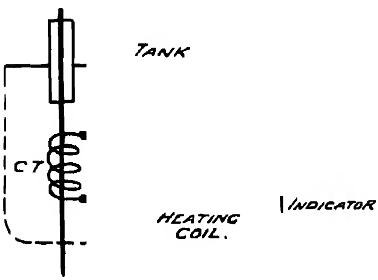


FIG. 148. Transformer winding temperature indicator.

Possibly the most outstanding development in relation to transformers is that connected with impulse phenomena. The practice of specifying very heavy reinforcement of insulation between turns adjacent to the line has been largely discredited. There is every justification for demanding a reasonable impulse strength for a transformer winding, but the method of producing the desired result should

be left to the designer. The fundamental factor in achieving the best possible distribution of voltage through a transformer winding is the appropriate distribution of the electrostatic capacity and it is possible to produce the desired result with a simple winding arrangement without shields, except for a small electrostatic shield facing the first coil,

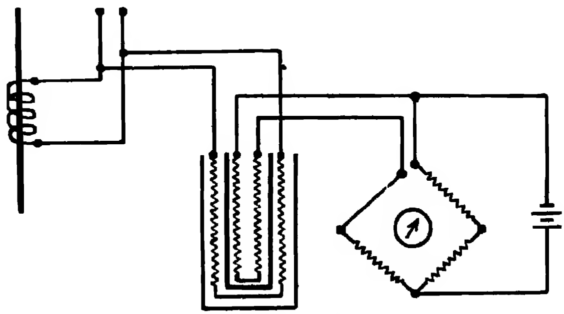


FIG. 149. Bridge-type winding temperature indicator.

and with only a comparatively low level of insulation between turns. Since the impulse strength of a transformer is the best criterion as to its capability of withstanding transient conditions that occur in, it is

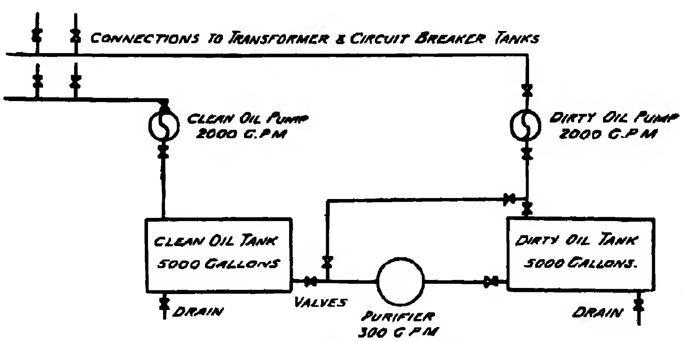


FIG. 150. Oil filtering and storage equipment.

anticipated that in due course routine impulse testing may become standard practice.

Mining Transformers. The usual design features are applicable to both surface and underground transformers, the main difference being the more robust construction of the latter. B.S.S. 335

covers the requirements of non-flameproof underground and surface transformers, and also flameproof and bell-signalling transformers. The scope of this specification may be summarised broadly as :

(1) Non-flameproof transformers for underground service up to :

300 kVA—Three-phase.
50 ,, —Single-phase.

(2) Flameproof transformers up to :

3 kVA—Three-phase.
5 ,, —Single-phase.

(3) Any size for use above ground at the surface of the colliery.

(4) Transformers for use above ground at the surface of the colliery.

Attempts have been made to standardise certain items such as : kVA ratings ; primary and secondary voltages ; adjusting tappings ; cable boxes and cable-box flanges ; overall dimensions ; and tank details. The standard sizes recommended in this specification are :

Non-flameproof type :
Single-phase—10 ; 15 ; 25 ; and 50 kVA.
Three-phase—10 ; 25 ; 50 ; 75 ; 100 ; 150 ; 200 ; 250 ; and 300 kVA.

Flameproof type :
Single-phase—1 ; 2 ; 3 ; 4 ; and 5 kVA.
Three-phase—1 ; 2 ; and 3 kVA.

For surface type transformers the ratings may be chosen from the standard sizes given in B.S.S. 171. A distinction must be made between flameproof mining transformers and non-flameproof underground mining transformers. The former may be installed in almost any situation in a mine where electric power is permitted, whereas the latter may only be installed in a non-danger zone. In practice, flameproof transformers are generally as follows :

Upper limits of kVA :

5 kVA Single-phase—33,000 volts.
3 ,, Three-phase— 700 ,,
2 ,, ,, ,, —33,000 ,,

Any unit of larger rated output is of the non-flameproof underground mining type for installation in a non-danger zone. Flameproof units may be of the air-cooled (dry), compound or oil-immersed types. Non-flameproof transformers, irrespective of their ratings, are permitted in mines where naked lights are allowed. The essential

features of underground mining transformers are safety, robustness and simplicity. Mining type transformers for underground working should be very strong mechanically so that they can resist the very rough transportation in the pit and meet the operating and other difficulties thus peculiar to mining conditions ; and they must be electrically safe in all respects. The core and windings should be rigidly braced in the tank to prevent undue movement during transport, under all conditions peculiar to mining work. Particular attention should be paid to cable box design and construction to facilitate removal and replacement without the necessity for breaking down the sealing chambers or lifting the tank cover. Such features expedite extensions and the moving forward of plant as necessitated by coal mining. The tank is of mild steel welded construction and perfectly oil-tight, but not intended to withstand internal explosion, the exceptions being the smaller flameproof units. In view of the restricted headroom in the majority of underground working places—also shaft diameter and facilities on cage for handling—it is necessary to keep the transformers within prescribed limits. Typical details are given in Table 16.

TABLE 16. *Mining Transformer Data*

Number of core limbs.	kVA.	Length in.	Width in.	Height in.
3	75	58	40	45
	100	60	41	48
	200	65	46	52
5	75	60	39	43
	100	66	40	40
	200	69	44	47
8	75	84	37	36
	100	89	38	37
	200	99	41	39

The usual three-phase transformer has three limbs, but to effect a reduction in height use is made of the five-limb type, and in very special cases eight limbs. By limiting the height of the limbs it is necessary to reduce their sectional area to accommodate the number

of turns normally required for the windings. To compensate for this reduction in limb section it is necessary to provide other parallel iron circuits to maintain the flux density within design limits. Breathers are not fitted to underground transformers on account of the liability to draw in fine coal dust.

To protect the lower voltage system being accidentally charged from the higher voltage system, it is customary to earth the neutral point of the former at the transformer, either direct or by way of a resistance or, alternatively, include a spark-gap arrangement. Difficulties arise with an insulated system, but these may be overcome by including an earth shield between the higher and lower voltage windings, or, alternatively, using a static earthing device. A copper sheet of thickness not less than 1/64th in. and earthed, may be used but is not recommended. A static earthing device consists of an insulated disc connected between the lower voltage windings and earth. For mining transformers of voltage ratio 3,300/400 volts, the disc must break down at a figure not much above the lower voltage, and it is not easy to obtain a reliable insulating disc which will do this.

The use of oil is dangerous in mines because of its inflammability, and the great density of smoke and gas produced in the event of transformer breakdown. It seems then that the transformer to be used underground should be of a non-inflammable type, or at least give off neither smoke or gas in the event of breakdown. The air insulated transformer has been adopted in some mines, but the air in a mine is usually saturated with water and loaded with dust and unless the transformer is continuously under load there is a risk of moisture condensation which would lead to breakdown. Transformers of the Pyranol type—using Dielectrol—were tried on the Continent when oil was in short supply. Chlorinated dielectrics were used, but they acted as solvents ; only bakelite suitably polymerised is not attacked. In the event of an internal arc certain chlorinated dielectrics cause the release of chlorine and hydrogen and if there is a surplus of the latter the atmosphere will eventually become more charged with fire-damp. To overcome such difficulties the quartz-filled transformer has been developed. In this design the oil is replaced by quartz which takes over the function of oil to remove the heat from the windings by thermal conductivity. It meets all the requirements of security, mechanical strength, electrical safety and flameproofness. Quartz sand has been used because of the following qualities : permanent and non-inflammable ; very good electrical insulation ; convenience of handling ;

it is a raw material easy to buy and stock. The choice of a solid material as a cooling medium was made, having in mind the handling and transportation of the transformer which can be done in any position—vertical or horizontal. Quartz is a neutral element which does not vary with heat or time, and is also non-inflammable. No maintenance is necessary ; the co-efficient of expansion of quartz is almost the same as that of iron and the unit is not subject to breathing ; the surrounding air does not penetrate to the interior of the tank ; thus the unit is almost moisture-proof. Even under short-circuit tests or in service, no variation of pressure higher than 4 p.s.i. has been recorded and this is one more reason for not having any breather. Earthed metal screens are placed between the H.V. and L.V. coils. Quartz is a very efficient material in respect of fire-damp, a small thickness being sufficient to prevent any propagation of flame, as well as fumes because it acts as a strong filter. Quartz does not suffice to remove the heat from the centre of the active parts to the sides of the tank, therefore metal screens are interlaced in the windings to absorb the heat by radiation and transmit it to the quartz through their large contact surfaces. The magnetic cores are placed horizontally in the same vertical plane ; the tank has inside cooling fins and carries boxes for the incoming and outgoing cables ; the quartz is used in the form of fine grains which permits of easy filling. The tank is set on four wheels and has a shock absorber. The technique of calculating the correct conditions due to the copper screen is different to the one used when considering air or oil-filled transformers. Typical temperature rises on three sizes of quartz-filled transformers are :

125 kVA	—	H.V. 57° C.	—	L.V. 59° C.
150 „	—	„ 57 „	—	„ 55 „
200 „	—	„ 60 „	—	„ 51 „

The maximum allowable temperature rise in France is 70° C. The quartz transformer is usually provided with a thermostatic device for safety and it is generally more able to withstand the forces resulting from short circuit. The quartz which slips into every little space, and especially between the coils, gives a mechanical strength to the active part of the transformer which is exceptional. That is not the case with oil, air or dielectrol. Practical tests have proved that an explosion of a quartz transformer, due to a short circuit, takes place without external flame and without damaging the exterior of the tank. Actual short-circuit tests were made on a 125 kVA, 5,000 V $\pm$ 5 per cent./500 V

transformer. Six consecutive tests were made with an interval of 3 min., each test lasting 1 min. 25 secs. under the primary voltage of :

(1) 5,000 V—2,500 A
(2) 6,000 V—2,800 A
(3) 7,000 V—3,500 A
(4) 10,000 V—4,700 A
(5) 15,000 V—7,000 A
(6) 16,000 V—7,400 A

The secondary was short-circuited and the short-circuit R.M.S. currents are given.

The oscillagrams showed that everything was in order and normal.

Mobile type sub-stations have also been made up with these units. The advantages of the quartz-filled transformer are : Incombustibility and inalterability of the quartz ; remarkable behaviour in fire-damp atmosphere ; internal absorption of eventually produced smoke ; maintenance is almost negligible ; ease of installation on site ; easy transportation in any position and very good performance under short-circuit conditions. There are many hundreds of these units in commercial service in France and Belgium.

Bell-signalling transformers come within the scope of mining regulations, and the principal features are : the secondary (R.M.S.) voltage should not exceed 15 volts ; a non-inductive resistance should be included in the apparatus to limit the secondary short-circuit current to 1·6 amps. maximum ; the self-induction of the unit should not exceed 0·001 henry ; with a current equal to twice the normal short-circuit value, the spark on making or breaking the secondary circuit should not ignite an explosive mixture. Such transformers—certified flame-proof and intrinsically safe by the Mines Department, and suitable for connection to medium and low-voltage 50-cycle systems—are made. Bells and relays designed to operate on 15 volts A.C. may be used with such equipments.

Parallel Operation. For satisfactory parallel operation certain conditions must be fulfilled :

(1) The phase rotation or order of voltage rise—R.Y.B.—on the terminals of the transformers must be identical.

(2) The polarity of the transformers must be the same. If zero voltage is obtained across all pairs of similar terminals, then the phase rotation as well as the polarity are the same in each case.

(3) Voltage ratio must be the same.

(4) Phase displacement between the primary and secondary vectors must be the same.

(5) The impedance voltage drop should be the same for correct sharing of load. The percentage resistance and reactance voltage drops should also be the same.

Transformers are tested and marked for polarity before leaving the makers' works, and no difficulty should be experienced in arranging

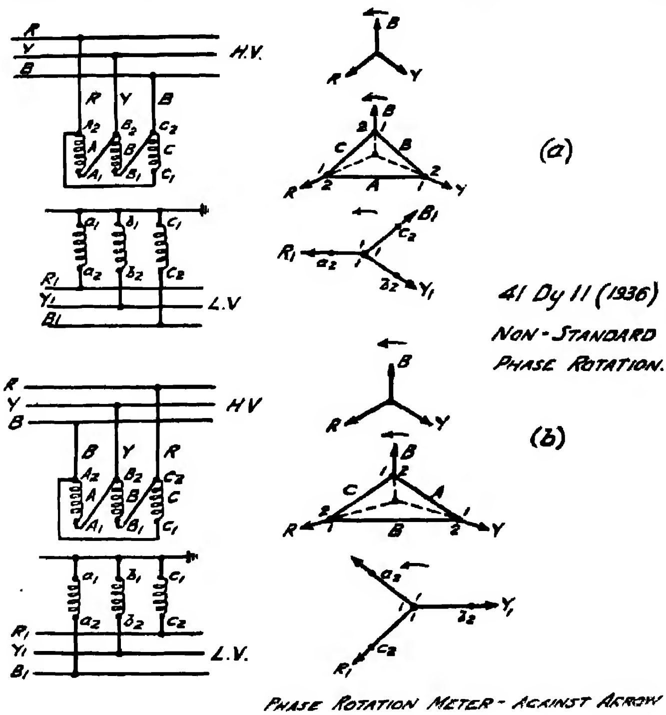


FIG. 151. Transformer vectors.

them for parallel operation. Should new transformers be required to work in parallel with unmarked existing transformers, it is necessary to check the polarity of the latter to avoid cross-over of cabling and connections. If the namê-plate particulars are missing, it is then necessary to obtain these from the maker, and consider them in relation to the new transformers. Time will be saved in changing over higher voltage connections and, possibly, breaking down of cable boxes. B.S.S. 171—1927 and 1936 give the necessary information relating to transformers, and should be studied before ordering and installing

new transformers. The three-phase units are divided into four groups, each group having three different combinations of higher and lower voltage windings. Any transformer in one group will operate in parallel with another unit in the same group, but transformers in one group will not parallel with transformers of another group.

For parallel operation of three-phase transformers the inter-phase connections may be grouped :

(*a*) Star/Star
Delta/Delta
Delta/Inter-Star
} These will parallel, if the inter-phase connections are suitably made.

(*b*) Delta-Star
Star/Delta
Star/Inter-Star
} These will parallel.

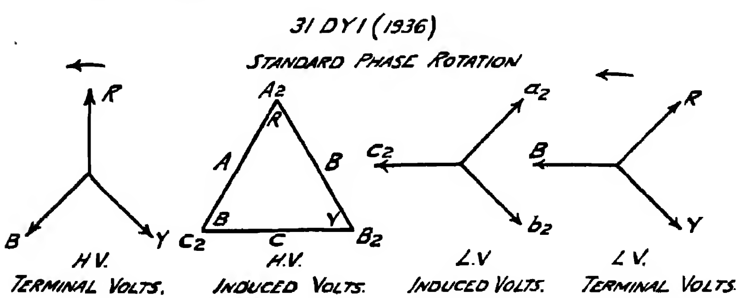


FIG. 152. Transformer vectors.

Four main groups :

Main Group No. 1—Zero Displacement.
" " " 2—180° Phase Displacement.
" " " 3—30° Phase Displacement Lagging.
" " " 4—30° Phase Displacement Leading.

Each group has three methods of inter-phase connections for the same phase relationship between primary and secondary sides, and transformers connected in one of the methods in a particular group may be paralleled with transformers having connections made to any other arrangement covered by that group. Further, by arranging the external connections, any method in group No. 3 may be paralleled with any in group No. 4. Therefore, a 30° lag in phase displacement may be changed to a 30° lead by suitably connecting the transformer line terminals to the primary and secondary systems.

Consider a delta-star transformer, Fig. 151, which is to operate in parallel with another belonging to the same group. There are three different arrangements possible from which to choose for the second transformer, namely :

	R.	Y.	B.	R.	Y.	B.	R.	Y.	B.
H. V. .	A_2.	B_2.	C_2.	B_2.	C_2.	A_2.	C_2.	A_2.	B_2.
L. V. .	a_2.	b_2.	c_2.	b_2.	c_2.	a_2.	c_2.	a_2.	b_2.

These are useful when the lower voltage cables or connections are large and a cross in connections is best avoided. The question of phase rotation of the supply also appears to add to the confusion which may arise when connecting transformers for parallel operation. Reversing the phase rotation of supply reverses both the phase rotation and polarity, but the order in which the transformer terminals attain their maximum e.m.f. is an important factor. With transformers having differently connected primary and secondary windings, *e.g.* delta-star and star-delta, a change of external connections to the primary affects both the phase sequence (rotation) and the polarity of the induced secondary voltages. A reversal of internal winding connections on either primary or secondary only, produces a reversal of polarity without altering the phase rotation. In practice, both standard phase rotation, R.Y.B. (Fig. 152), and non-standard phase rotation, R.B.Y., are to be found, and the polarity may be additive or subtractive. It is additive when the coils—primary and secondary—are wound in the same direction, that is, the induced secondary e.m.f. is in the direction as the primary volts producing it. Coils wound in opposition give subtractive polarity.

Special Types. Attention has been directed to the development of fire resisting transformers, the whole of the insulating material used in their construction being non-ignitable. They are immune from damage caused by short circuits or open circuits in the windings, or insulation failure, and are capable of carrying heavier loads for longer periods than oil-cooled units. The transformers are air-cooled and operate satisfactorily at temperatures of about 150° C. without damage, or showing deterioration in the insulating material. More space is required, but oil troubles and fire risks are eliminated and maintenance reduced. Gas-filled (nitrogen) transformers have been used in America operating at a pressure of 100 to 150 p.s.i. Other designs employing non-inflammable filling media are used, a typical example being Permitol. They are designed to comply with B.S., but the coils and

core materials, although similar to oil-immersed transformers, are treated and are unaffected by the filling. The specific inductive capacity of Permitol is almost the same as that of the solid insulations used in the transformer, and stress distribution is improved, bringing about a saving in material. Tanks are of normal construction, but the tubes are of special section to reduce the filling content, and the sampling valve is placed at the top of the tank, for the liquid is heavier than water. The liquid is practically non-hygroscopic, but should any moisture get into the tank it will float on the surface. Conservators and breathers are not required on hermetically sealed units. A relief diaphragm is fitted, and a relief pipe connecting the vent to the outside can be included. Gases given off are non-poisonous and non-explosive, but should not be allowed to accumulate in a building. The cost of transformers using Permitol filling is higher, but where oil filling constitutes a serious fire hazard then such a filling can be justified.

Another type used on distribution networks is the " buried " type, which is installed below ground level, and depends largely for its cooling on the thermal conductivity of the surrounding ground. The tanks may be corrugated to afford greater area for heat dissipation. The lower portion of the transformer is buried direct in the ground, but the top is accessible by way of a manhole. The switch-fuse and cable glands are also accessible through the manhole and the unit can be disconnected and removed. The tank is tapered to facilitate removal and is treated to render it impervious to moisture. Hermetically sealed oil filled transformers are also used and special expansion arrangements are included. To ensure that the correct quantity of oil is used the final filling is carried out with the transformer in a hot condition, thus preventing the expansion chamber being over-strained when the transformer attains its maximum temperature.

Scott-connected Transformers. The Scott connection is used where it is necessary to change the supply from three-phase to two-phase, or *vice versa*, and is also useful for obtaining single-phase. With two equal single-phase loads on the two-phase side, a balanced load is obtained on the three-phase side. Two single-phase transformers are usual (Figs. 153 and 154), but on smaller units the windings are accommodated in one tank. To facilitate interchange each transformer can be of identical winding design, the tapping points enabling conversion to 100 per cent. of 86·6 per cent. units. The primaries of the two transformers are Tee-connected on the three-phase side, Fig. 155,

whilst the secondaries are separate and deliver a true two-phase supply. The primaries are wound for voltages in the ratio of $1 : \frac{\sqrt{3}}{2}$ or $1 : 0{\cdot}866$, since the primary of the second unit has a reduced line voltage. FC is 90° out of phase with ED, and E_{2B} out of phase with E_{2A}. The voltage given by the secondary of the second unit is increased relatively to that of the first in the ratio $\frac{2}{\sqrt{3}}$. This equalises the voltages, which are already out of phase with each other. The current in the leg CF, *i.e.*, $I_1 = \frac{I_2}{0{\cdot}866} \cdot \frac{E_2}{E_1}$, and is in phase with the voltage

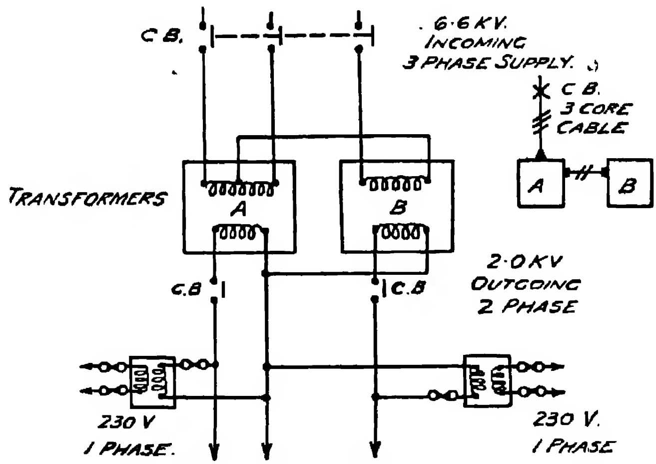


FIG. 153. Scott transformer units.

CF. This current divides equally at F, one half flowing in each side of the winding ED, so that the resultant current in FE and FD is the vector sum of I_1 and $\frac{I_2}{2.\ 0{\cdot}866} \cdot \frac{E_1}{E_2}$, *i.e.*, I_1 and $\frac{I_1}{2}$. As these currents are 90° out of phase, the resultant $= \sqrt{I_1^2 + \frac{(I_1)^2}{2}}$ and makes an angle with the voltage vector ED equal to $\tan - 1.\ \frac{1}{\sqrt{3}}$ 30°. The line currents are therefore equal and in phase with the phase-to-neutral voltages EN, DN and CN. At unity power factor load, the power

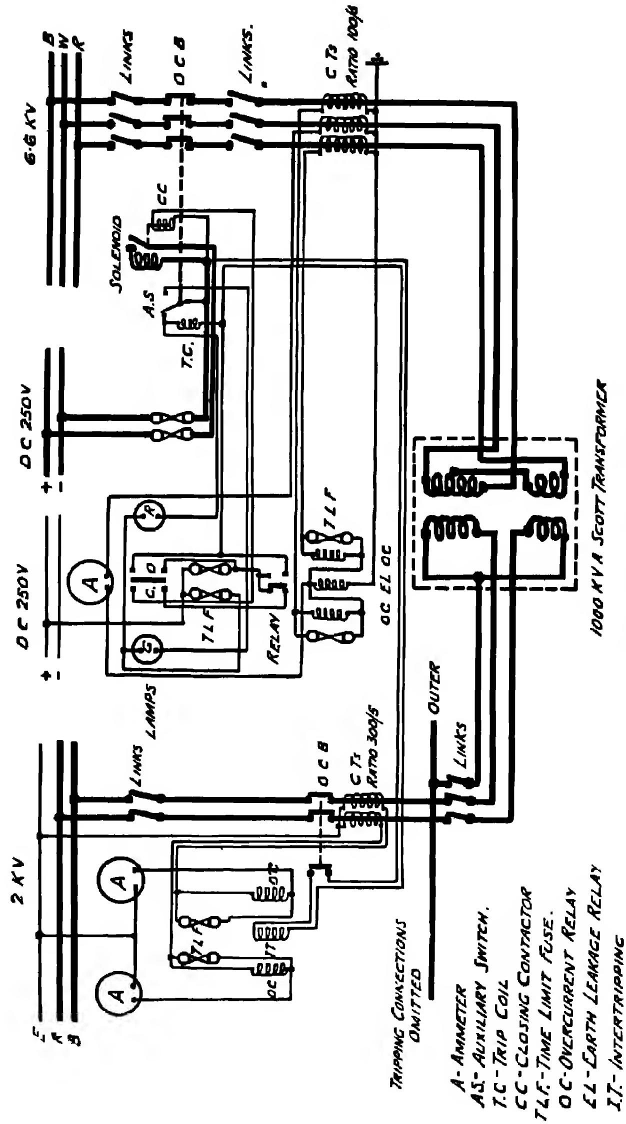


FIG. 154. Scott transformer connections.

factor of the currents in windings EF and DF is 0·866, the current leading the voltage in one half and lagging in the other, while the current in CF with respect to the winding voltage is at unity power factor. The output on the two-phase side = $2E_2 . I_2$ and on the three-phase side the input = $\sqrt{3}E_1 . I_1$. Neglecting losses $2E_2.I_2 = 3.E_1.I_1$. The kVA capacity of the (100 per cent.) three-phase side of $T_1 = E_1I_1 = 2E_2I_2/\sqrt{3}$ which is equal to $1/\sqrt{3}$, or 57·7 per cent. of the

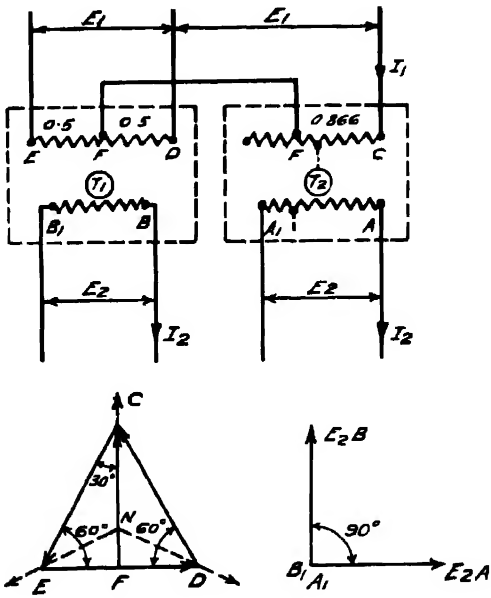


FIG. 155. Scott transformer connections.

capacity of the whole transformer, *i.e.*, $T_1 + T_2$. The kVA capacity of the (86·6 per cent.) three-phase side $= \frac{E_2 . \sqrt{3}. I_1}{2} = \frac{\sqrt{3}}{2}.\frac{2E_2. I_2}{\sqrt{3}} = E_2. I_2$, *i.e.*, one half of the total capacity. Therefore, both windings on the two-phase side, and also the primary winding of the 86·6 per cent. unit (T_2) have capacities equal to half the normal kVA output, while the primary winding of the 100 per cent. unit (T_1) must have a greater capacity in order to carry the wattless component of the current it is required to carry. There is a difference in the impedance

of the three legs of the primary windings, and also different power factors of the currents which result in different impedance voltage drops, thus causing slight voltage unbalancing. This transformer can be used for single-phase supply such as furnaces and domestic loads. With a unity power factor load on the two-phase side of the 86·6 per cent. unit only, the current flowing in the three-phase side is also single-phase, the primary current I_1 flowing through CF and dividing equally at F to flow through windings FD and FE. With a unity power factor load on the two-phase side of the 100 per cent. unit only, the primary current I_1 flows in windings ED only.

Rectifier Transformers. These are of special design in both electrical and mechanical details. The principal differences are : additional insulation of secondary windings ; special bracing of windings and connections ; iron circuit designed to control leakage flux ; positioning of the different windings and duplication of secondary windings. The additional insulation of secondary windings is to withstand abnormal voltage surges to which they may be subjected and surge arrestors may also be connected across each winding. Special bracing is applied to the windings and cables to prevent movement and consequent damage due to heavy unbalanced currents which may flow during abnormal rectifier conditions when back-fire occurs. Multiple secondary windings are necessary for connection to the respective anodes. The relationship between the kW rating of the rectifier and the kVA rating of the transformer depends chiefly on the number of phases used. Some of the transformer windings used are illustrated in Chapter VII.

Many transformers of 2,500 kW at 3,000 D.C. have been supplied and larger units are now practicable. In the case of a power transformer the load current is virtually sinusoidal and it is balanced by a primary current of similar wave form. Neglecting excitation and impedance losses, therefore, the primary and secondary are the same. Owing to the fact that each rectifier anode conducts only for that part of the cycle during which it is at a higher potential than the other anodes, the secondary winding to which it is connected carries current for a part of each cycle only, the current being blocked by the valve action of the rectifier for the remainder of the cycle. During the time the current does flow it is ideally a direct current of constant value and is consequently not sinusoidal but of substantially rectangular wave form. In practice, owing to the various reactances present in the circuits, the current in each winding takes an appreciable time to build

up and die away, and consequently the actual secondary current wave departs somewhat from rectangular formation. The transformer windings are usually arranged so that secondary winding currents supplied to more than one anode are balanced at least in part by the current in a common primary winding, so that the primary current wave shape differs from that of the secondary, but is still not sinusoidal. On account of the non-sinusoidal nature of the primary and secondary currents their R.M.S. values, upon which the thermal design of the rectifier transformer must be based, are increased, and consequently the kVA rating of the secondary windings is greater than that of the primary windings, due to the greater departure of the secondary current wave form from a sinusoidal wave. For a similar reason the primary power factor is less than unity, and the primary current wave contains a number of odd harmonics. These harmonics are inherent in rectifier equipment, but are not usually very important except when the total rating of the rectifier equipment installed is a considerable proportion of the supply system capacity. When it is necessary to connect two rectifier bulbs or tanks to one transformer in order to give the load rating required, the transformer is usually provided with two distinct secondary windings, one to supply each tank ; but if more than two tanks are to be fed from one transformer they each may be connected either to a separate secondary winding, in which case anode reactors or anode transformers are interposed to ensure correct load sharing. The arrangement to be adopted depends upon several factors among which primary voltage and total output required are important. A characteristic in the design of rectifier transformers with which special care must be taken is that known as commutating reactance. This is the reactance in the windings encountered when the current is transferred from one anode to the succeeding anode. It is usually desirable that all the values of this reactance round the operating cycle should be approximately equal, otherwise unequal anode loading will result. This equality of commutating reactance values is obtained by a careful physical arrangement of the parts of the secondary winding, and it is especially important in the case of windings arranged for twelve-phase working. Particular attention is given to the design and bracing of the coils and the connections between the coils and terminals. This is very important when two or more equipments are operating in parallel in the same sub-station, because of the possibility of feed-back from the D.C. side of the healthy equipment. The primary and secondary windings are arranged so that magnetic sym-

metry is preserved as closely as is practicable irrespective of the voltage tapping in use, in order to keep end-thrust forces to a minimum. For the same reason the total range of tappings specified for rectifier transformers should be as small as possible consistent with operational requirements. The coils are very rigidly braced both radially outwards from the core and from one another, and also in an axial direction between the top and bottom clamps.

Auto-transformers. The principle will be understood from Fig. 156. They are seldom used on sub-station equipments, but are employed on industrial works' systems. The primary and secondary currents act in opposition, and the resultant current I_R is the vector sum of the two, being approximately equal to the arithmetical difference, *i.e.*,

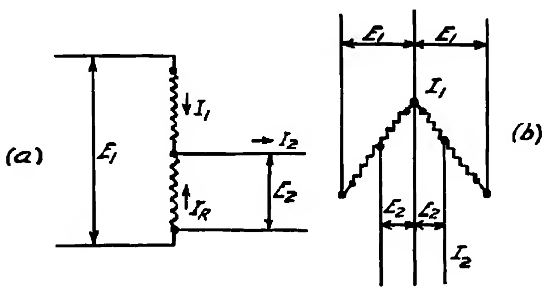


FIG. 156. Auto-transformer connections.

$I_2 - I_1$. There is a saving in copper compared with the double wound transformer, especially where the transformation ratio is low, varying according to $\frac{N-I}{N}$, where N is the ratio of transformation. The great disadvantage is the direct electrical connection between the higher and lower voltage windings.

Interconnected Star Transformers. These are used for obtaining a system earthing point, and also affording a supply for auxiliaries. A neutral point is available on the primary and secondary windings, only one of which should be earthed. The reactance of the interconnected star windings is low, and therefore provides a low impedance path for the flow of single-phase earth fault currents. Due to the interconnection on the secondary side, the voltage is free from third harmonic currents and has the advantage of being able to supply an unbalanced load with very little voltage unbalancing.

REACTORS

Reactors limit the current which flows in a circuit under fault conditions, and are of the air and iron core types. The air core reactor consists of several layers of stranded copper conductor, supported in porcelain or concrete separators. A constant reactance is obtained for all current values, and they are cheaper than iron core oil-immersed reactors. They are bulky, and must be arranged with reasonable clearance from surrounding metalwork to prevent eddy currents being set up in the metalwork. They are placed in cells adjoining or immediately below the switchgear, and individual units must be locked off. Oil-immersed reactors are popular, probably due to the fact that they require less building space, are suitable for outdoor service, and immune from external magnetic fields.

Reactors should be designed to carry without damage for a specified time the maximum through short-circuit current with the total kVA available on the input side, and have as nearly as possible a straight line characteristic up to this value of current. Magnetic saturation should be avoided under all fault conditions if the limits of protection are not to be impaired. With windings of laminated or stranded conductors, the strands are insulated to minimise eddy current losses. The insulation of the end turns and connections is reinforced and braced to withstand the effect of surges and switching transients. The windings are either magnetically or electrically shielded to prevent flux entering any part of the coil clamping structure or tank. Laminated iron shields may be used when the ratio of short-circuit current is less than 30 to 1, and copper shielding above this value. The ratio between the normal current and maximum short-circuit current influences the thermal design of a reactor, and if a reactor is to give 5 per cent. reactance, and no other reactance is in the circuit protected, the short-circuit current is twenty times normal, in which case the short-circuit conditions probably determine the thermal design. Should additional reactance in the circuit limit the maxium short circuit to, say, twelve times normal, then normal load conditions have the greater influence on the design. This feature also affects the normal load loss, and to reduce the running costs it may be desirable to have a low load loss by using a larger conductor, which further improves the thermal conditions under short circuit.

The fittings are similar to those supplied with transformers, and reference should be made to B.S.S. 171—1936. Oil-immersed reactors require but little attention and are not so prone to flash-over and

breakdown as the air core type, although the latter have proved very reliable in service. The principles of transformer layout also apply to reactors. The following data relate to a 33 kV, 6,250 kVA (10 per cent. on 62,500 kVA) three-phase oil-immersed reactor :

Maximum through short-circuit current to pass for fifteen seconds .	10,930 (R.M.S.) amps
Type of shielding :	
Outside coils . . .	Magnetic.
Over ends of coils . . .	Non-magnetic.
Approximate through current to cause saturation of shields . .	11,000 amps.
Total sectional area of winding conductor .	0·69 sq. in.
Size of each strand :	
Width	0·32 in.
Thickness	0·085 in.
Current density in conductor and end connections . . .	1,600 amps. per sq. in
Insulation between strands .	Paper.
Insulation between conductors and frame	Presspahn.
Total weight (single-phase unit) .	10·5 tons.
Switchgear before reactor . .	1,500 M.V.A.
,, after ,, .	750 ,,

Arc Suppression Coils. These are used for earthing transformer neutral points and overhead line systems to suppress arcing faults. The coil (Fig. 157) is a method of earthing the neutral of the system through a reactance, so interruption of supply is minimised and fault current restricted to a safe value. Under normal conditions, the capacity currents of a three-phase line are balanced and do not give rise to a resultant current in the neutral. Should an earth fault occur on one phase, then the voltage of the other two phases is raised to full voltage above earth, and their capacity currents are increased to $\sqrt{3}$ times normal, the resultant capacity current through the earth fault leading the voltage of the faulty phase by 90°. The coil reactance is such that if a current equal to the resultant capacity current flows through it, the voltage drop will equal that of the normal phase voltage and a current lagging the voltage of the faulty phase will result. The

two currents should be equal and opposite for ideal operation, thus giving zero resultant at the fault and so preventing the maintenance of arcing. The resistance losses in coil, transformer windings and dielectric, make it almost impossible to obtain this ideal, but satisfactory practical results have been obtained. Before installing an arc suppression coil it is essential to ensure that all neutral points are insulated for full voltage to earth. With graded insulation it is possible for the more lightly insulated sections of the transformer windings near the neutral to fail under earth fault conditions. The mechanical construction of the coil is similar to that of an oil-immersed single-phase transformer and may be of the two- or three-limb type. Air gaps are introduced into the magnetic circuit and flux densities chosen to obtain the desired characteristics. The current/voltage curve of the coil is

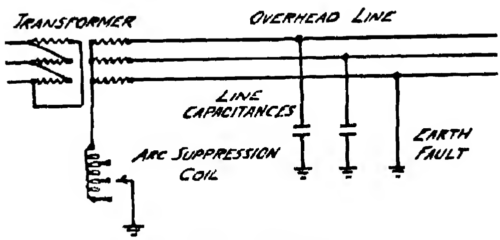


FIG. 157. Petersen coil.

important, and the portion of the curve up to full load rating of the coil should be as straight as possible so as to maintain the ratio $\omega L = \frac{1}{\omega C}$ constant within reasonable limits. Above that value the curve should bend over as quickly as possible.

There are two methods of coil rating : short period (about five minutes) under fault conditions and to switch out the faulty line after a few seconds' delay ; continuous working and allow a faulty line to remain alive with one phase earthed until such times that it can be repaired. To determine the size and design of coil it is necessary to know the line capacities or the equivalent earth fault currents. Tests can be made by isolating the neutral and measuring the current when one phase is earthed. Such readings are reported to be reliable, but tend to be high if taken at light loads with poor wave form, due to the inclusion of harmonic components which can be compensated by the suppression coil.

A voltage transformer is included for the operation of directional relays, also indicating and counting devices for recording coil operation. A current transformer energises a recording ammeter which shows the current flowing in the coil and the time it came into operation.

VOLTAGE REGULATORS

Induction Regulator. A three-phase induction regulator is similar in construction to an ordinary three-phase induction motor with wound rotor, except that the movable portion of the regulator is not free to rotate, its position being controlled by a small reversible motor operating through a worm reduction gearing. The primary windings P are connected in star (or delta) and the secondary windings S are in series with the line conductors (Fig. 158). The secondary is wound on the stator, as the two ends of each phase have to be brought out. The current is fed into and out of the rotor windings by flexible cable, since the winding is never rotated through more than 180 electrical degrees,

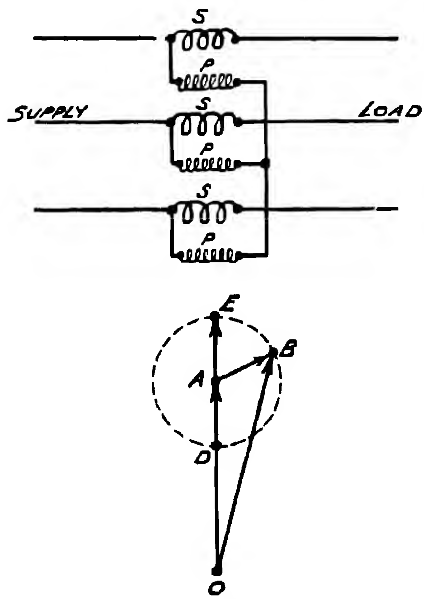


FIG. 158. Induction regulator connections.

e.g., a quarter of a revolution for a regulator with four poles. Consider a two-pole regulator with the primary windings P on the movable portion. The three-phase currents give rise to a magnetic field rotating at synchronous speed, thereby inducing in each phase of the stator winding an e.m.f. of magnitude AB. The phase of this e.m.f. in relation to the associated phase voltage OA of the supply can be altered by moving the rotor winding of the regulator relatively to its stator winding. This, however, does not vary the magnitude of the secondary e.m.f., so that if the secondary e.m.f. with a given position of the rotor be represented by AB, the voltage between the

star point of the supply and the load side of the regulator is given by OB. By altering the position of S in relation to P, the resultant voltage can be varied between the minimum OD and the maximum OE. The general applications of the induction regulator are :

(1) Boost and regulate the voltage of a feeder or transmission line ;

(2) Control the D.C. voltage of a rotary convertor ;

(3) Control the transfer of electrical power between two interconnected systems ;

(4) Facilitate voltage testing by providing a means of increasing the test voltage gradually.

The rating of a regulator may be estimated as follows :

A three-phase induction regulator is required for adjusting the

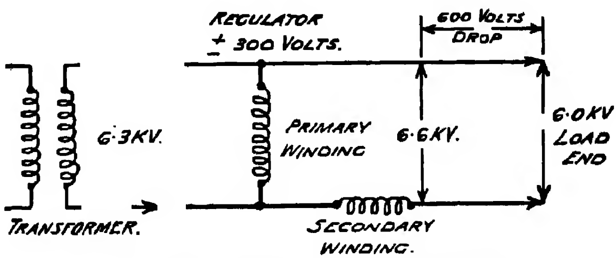


FIG. 159. Induction regulator connections.

voltage applied to a 750 kVA load by ± 10 per cent. of the normal voltage of 500 volts.

$$I = \frac{750.\ 1{,}000}{\sqrt{3}.\ 500} = 870 \text{ amps.}$$

The line voltage has to be varied ± 10 per cent., therefore the voltage to be induced in each secondary phase of the regulator $= \dfrac{50}{\sqrt{3}} = 29$ volts.

$$\therefore \text{ the kVA rating of each phase} = \frac{870.\ 29}{1{,}000} = 25$$

$$\therefore \text{ the total kVA of the regulator} = 25 \times 3 = 75$$

Alternatively, this could be found by taking 10 per cent. of the system loading, for the regulator has to be capable of supplying the additional kVA.

$$\therefore \text{Induction regulator rating} = 750 . \frac{10}{100}$$
$$= 75 \text{ kVA as before.}$$

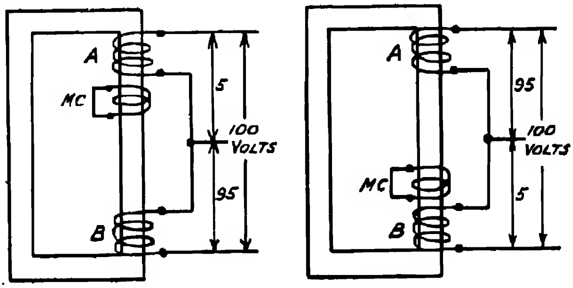


FIG. 160. Principle of moving coil regulator.

Assuming (Fig. 159) the voltage of load end of the line is to be maintained at 6·0 kV, and that the voltage drop at full load is 600 volts. The transformer at the sending end of the line would be arranged to give 6·3 kV to the line, *i.e.*, 6·0 kV plus one half of the voltage drop. On no-load the induction regulator would be in the negative position to subtract the additional 300 volts given by the transformer, whereas on full load it would be in the positive position to add another 300 volts, so that 6,600 — 600 will give the desired delivery voltage.

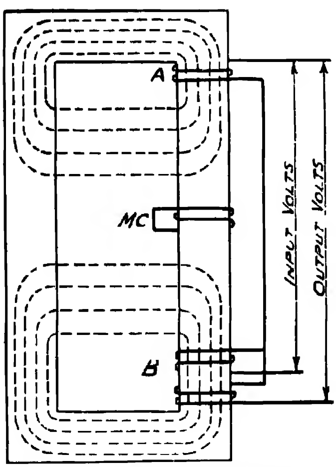


FIG. 161. Moving coil regulator.

Moving Coil Regulator. The construction of this type will be appreciated from Figs. 160–163. A novel feature is the short-circuited coil which moves up and down one limb of the core, its function being to prevent the passage of magnetic flux through it. The coil carries a relatively small current of high power factor. Due to the absence of voltage phase-displacement, moving coil regulators are suitable for interconnector voltage load distribution and power factor control. The regulator can operate in ring

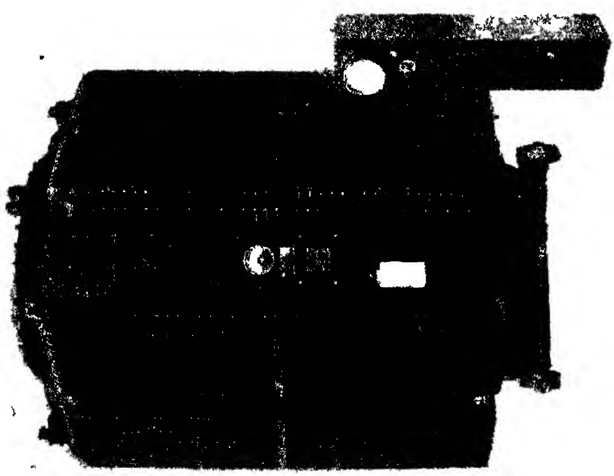


Fig. 162 Automatic moving coil voltage regulator, giving a 20 per cent voltage control in a 7,500 kVA 11 kV 3-phase circuit (Ferranti)

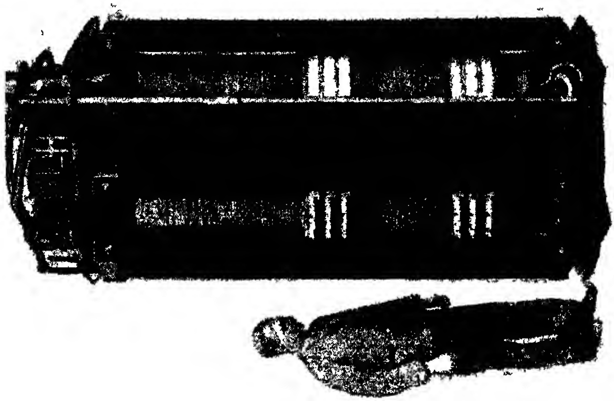


Fig 163 Internal view of regulator showing winding construction and mechanical operation.

mains involving reversal of power flow. The voltage control relay is actuated by the voltage between lines at the point of correction. Good load-balancing conditions are necessary to obtain maximum effect from voltage regulator and a static balancer is desirable.

On-Load Tap Changing. Considering the transformer formulae $\frac{E_1}{E_2} = \frac{T_1}{T_2} = \frac{I_2}{I_1}$ it will be appreciated that with a constant voltage E_1, value of E_2 can be varied by changing the turns ratio T_1/T_2. Tap-changing voltage control equipment enables the turns ratio to be varied by adjusting the number of turns on either the primary or the secondary windings, or both, without interrupting the load. When the number of primary turns is decreased, the inductance—which equals $\frac{\phi \cdot T_1}{I_1} \cdot 10^{-8}$ henries—also decreases, and the magnetising current increases, the opposite being the case when the number of turns is increased. During the process of changing the tappings, the current flowing in the shorted turns must be restricted by the insertion of a reactance or resistance. The centre portion of the primary (H.V.) winding is chosen as the currents to be dealt with are smaller and better electro-magnetic balance is maintained between the primary and secondary windings. Further it avoids weakening the additional inter-turn insulation provided at the ends of the winding. The voltage change per tapping is of the order of 1 to $1\frac{1}{2}$ per cent. When fitted to a delta-connected winding, the tappings are usually situated at the electrical centre of the windings. Here they escape the transient over-voltages to which the line end turns are prone, and at the same time the normal voltage between phases and from phase to ground is only one half of the line voltage. In a star connection the tappings may be situated near the neutral end of the windings ; with a winding designed for a solidly earthed neutral point, the neutral connection may be made at the switchgear, but it is the practice to provide some reinforcement to the neutral end turns and place the tapping sufficiently far into the windings to avoid this reinforcement. In either of these positions, tap switches with much reduced insulation can be used, *e.g.*, 33 kV equipment can be used on a 132 kV star winding. One method of carrying out this operation is by auto-transformer (Fig. 164) having a centre tap which is used to bridge the tapping points of the main transformer winding. By making the auto-transformer continuously rated its winding can be left in circuit across two taps, and using the centre

terminal of the auto-transformer as the line connection, additional voltage positions can be obtained. Fig. 165 illustrates the use of a

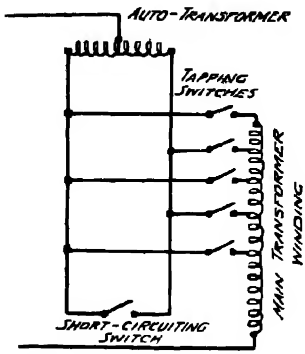


FIG. 164. Mid-point auto-transformer tap changing.

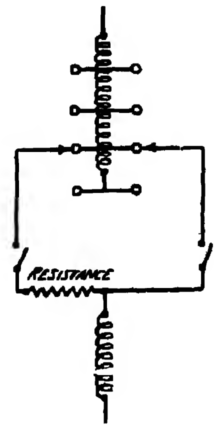


FIG. 165. Buffer resistance tap changing.

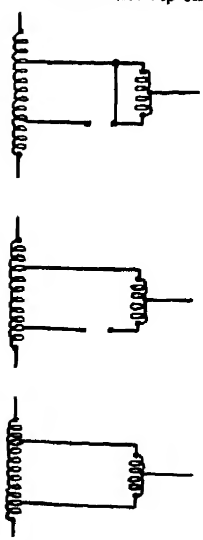


FIG. 166. Mid-point choke tap changing.

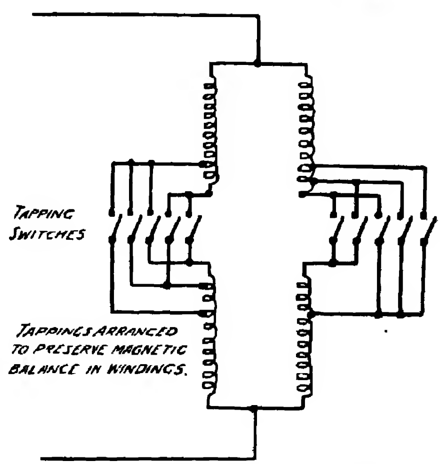


FIG. 167. Parallel winding tap changing.

buffer resistance designed to pass a circulating current equal to full load when it is connected across adjacent tappings. The advantages compared with the mid-point choke method are that the voltage

fluctuations are smaller and nearly in phase with the main voltage, and the contacts handle current at approaching unity power factor. Provision has to be made to guard against the resistance remaining in circuit and carrying current due to failure of the tap-changing gear when in an intermediate tap position. In the mid-point choke (Fig. 166) the value of the steps should be as small as possible, otherwise there may be severe disturbance to the system voltage. There is an out-of-phase voltage drop during the passage of load current through half of the choke, and this drop is equal to half the tapping voltage since the choke is designed to pass a circulating current equivalent to the full load current. Fig. 167 shows the parallel winding system. Figs. 168–170 show alternative methods.

A further method is the application of an induction regulator in place of the mid-point choke, and has the advantage of giving a smooth voltage change independent of transformer load. Tap-changing equipment includes switch contacts and a rather complicated system of mechanical control gear which necessitates periodic inspection and maintenance. This requires the equipment to be isolated from the line whereas an induction regulator does not.

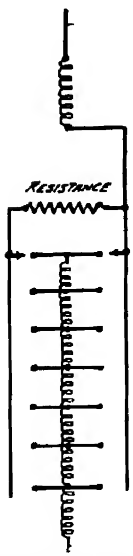


FIG. 168. Selector switching.

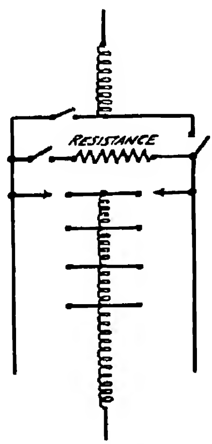


FIG. 169. Resistance with divertor switches.

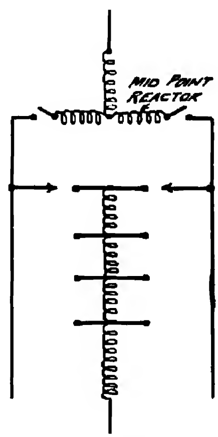


FIG. 170. Mid-point reactor with divertor switches.

The induction regulator is unaffected by frequent operation, but with a tap changer this generally implies increased maintenance.

Manual and automatic tap-changing equipments are at a disadvantage when operating on short circuits.

Induction regulators can withstand short circuits of forty times full-load current, and the driving motor thermal trips stop the regulator. The initial cost of the induction regulator is higher than the tap changer. One important aspect is that it is essential to guard against failure of supply during a tap change, especially where short-time-rated resistances and coils are used. One method is to provide a flywheel attached to the driving motor shaft, in which case the operation does not commence until the motor has reached full speed as determined by a centrifugal switch. The stored energy of the flywheel is then used to complete the tap-change operation. Spring-closing gear is in use, and alarm and emergency tripping circuits are included.

Fig. 171 shows a typical off-load tapping switch arrangement.

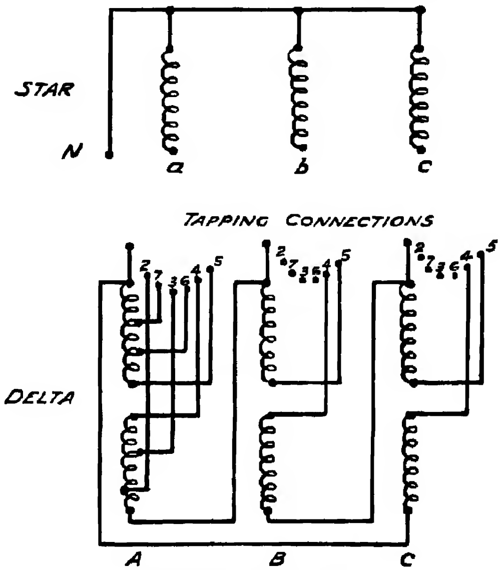


FIG. 171. Tapping connections for 1,000 kVA, 6,600/400 volt transformer.

Position of links.	H V. line volts per cent.	H V Tapping connections (phases A, B and C)	L V. volts phases a, b, and c).
1	95	2–7	400
2	97·5	7–3	,,
3	100 (6,600)	3–6	,,
4	102·5	6–4	,,
5	105	4–5	,,

Static Balancers. Network out-of-phase loading may be overcome by using interconnected-star balancers, Figs. 172 and 173, which may operate in conjunction with automatic voltage regulators. This can also be applied to single-phase three-wire distributors, when a mid-

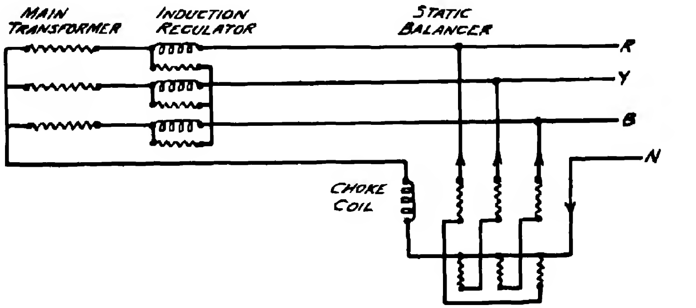


FIG. 172. Main connections for regulator/balancer.

point balancer is used. The interconnected-star balancer is essentially a one/one ratio three-phase auto-transformer with equal sections of winding on each limb connected in the interconnected-star manner. It is most economical to place the induction regulator at the supply

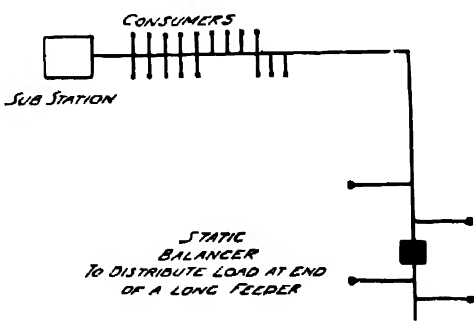


FIG. 173. Static balancer on feeder.

end of a feeder, and the balancer near the receiving or load end. Assuming an out-of-balance current of 45 amps. flows in the neutral, then each leg of the balancer would carry 15 amps., *i.e.*, the more lightly loaded lines would each carry an additional 15 amps., thereby

relieving the overloaded line by 30 amps. The nominal kVA rating of such a balancer $= \dfrac{I_N \cdot E_L \cdot \sqrt{3}}{3{,}000}$

Equivalent three-phase transformer rating $= \dfrac{k\text{VA}}{\sqrt{3}}$

Where I_N = neutral current
E_L = line voltage.

To overcome unsymmetrical loading it is preferable to install a number of small balancers near the load centres, instead of one large unit, but since the neutral must not be earthed at more than one point it is necessary to make it a continuous conductor throughout the system. Should the neutral conductor be broken, the voltage of one phase might rise to full line voltage to earth under fault conditions. A high impedance choke coil connected in the neutral in front of the balancer ensures continuity and compels the balancer to re-distribute the out-of-balance current.

Boosters. To overcome excessive voltage drop, particularly on rural distribution lines, boosters are used, Fig. 174. The action is similar to the induction voltage regulator, except that the boost voltage is fixed in both magnitude and direction, *i.e.*, positive boost. Automatic two- and three-stage boosters can be used and function with load variations by means of current relays and contactors.

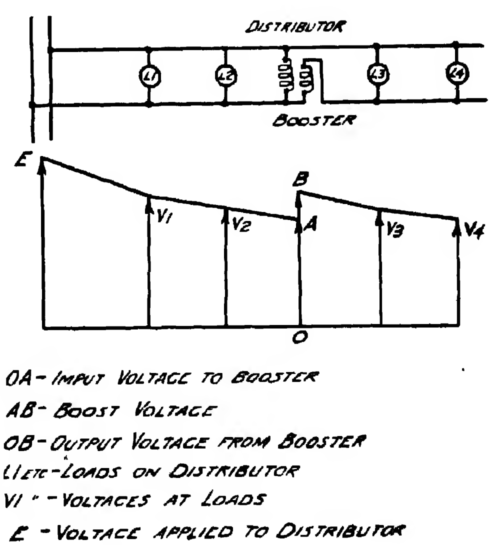


FIG. 174. Booster for maintaining voltage at end of distributor.

Transformer Data. Figs. 175 and 176 show typical transformer losses and costs.

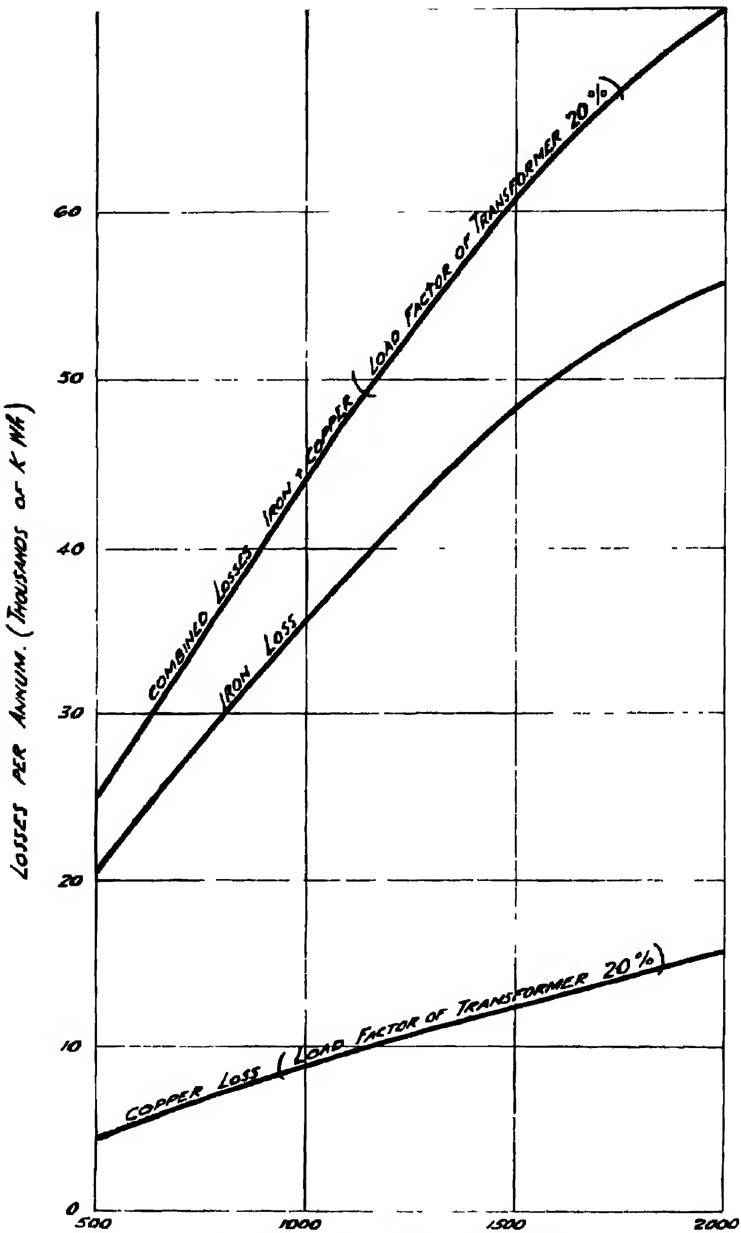


FIG. 175. Three-phase transformer losses.

Series Capacitor. This can be effective in reducing voltage drop if the circuit reactance is equal to or greater than the resistance and the

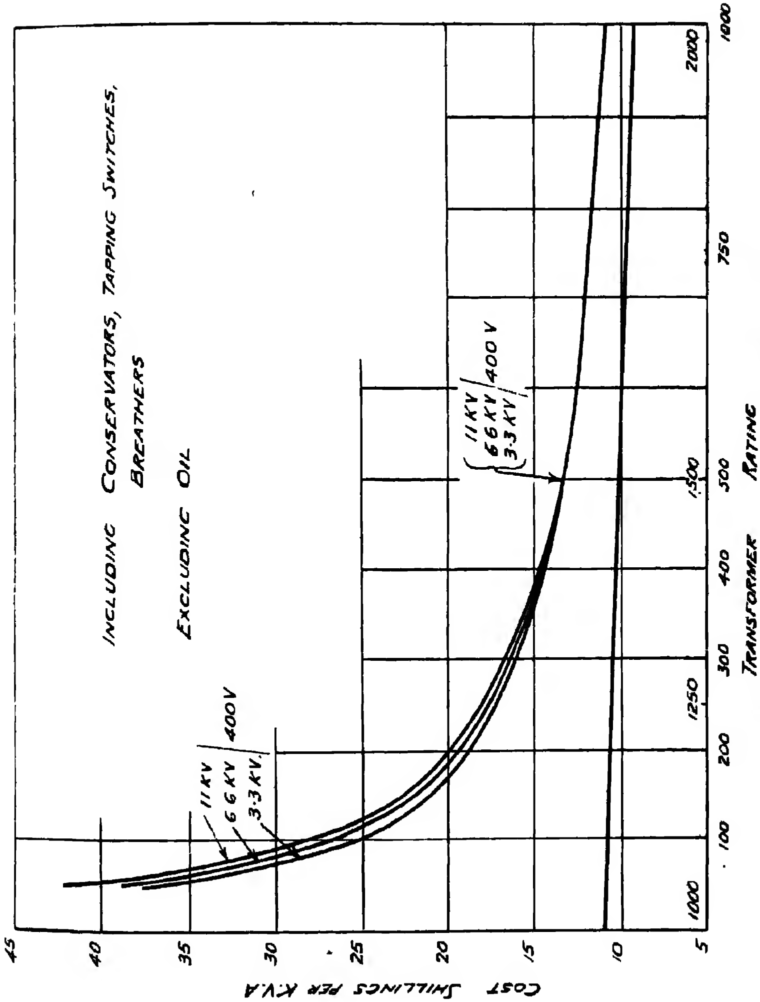


FIG. 176. Three-phase transformer costs (Type O.N. 1943).

current is at a low lagging power factor. An advantage is that its action is instantaneous whereas in transformer tap-changing and regulators the voltage must have fallen before the actuating relay will

operate. The disadvantages are : special insulation levels for higher voltages ; considerable momentary increase in voltage across the capacitor, with short circuit currents ; small continuous overcurrents cause deterioration of insulation. The series capacitor is not used on distribution networks except where low power factor loads such as welding plants and arc furnaces are connected.

Bibliography

W. E. M. Ayres. "The Application of the Induction Voltage Regulator," *Journal I.E.E.*, Vol. 69, 1931.

F. T. Beunell. "Rating Rectifier Transformers," *Electrical Times*, 26th September, 1946.

F. T. Beunell. "Rectifier Transformers," *Electrical Times*, 22nd April, 1948.

T. H. Carr. "Electric Power Stations," Vol. 2. (Chapman & Hall.)

,, "Failure of Reactors," *The Electrician*, 13th July, 1945.

G. O. Castell. "Transformer Overloads," *Electrical Times*, 2nd January, 1947.

R. M. Charley. "Recent Progress in Large Transformers," *Journal I.E.E.*, Vol. 69, 1931.

H. Diggle. "Applications and Construction of Transformer On-Load Tap Changing Gear," *Journal I.E.E.*, Vol. 81, 1937.

A. G. Ellis. "Some Notes on Transformer Practice with reference to Standardisation," *Journal I.E.E.*, 1946.

H. M. Goris. "Mining Type Transformers, using Quartz as a Cooling Agent," *Mining, Electrical and Mechanical Engineer*, September, 1948.

J. B. Hansell. "Protection of Distribution Transformers against Over-Voltages Produced by Travelling Waves," *Metropolitan-Vickers' Gazette*, 1939.

T. A. Ledward. "Transformer Diagrams," *Electrician*, 31st May, 1946.

J. E. Macfarlane. "Transformers in Parallel," *Electrical Review*, 3rd August, 1945.

F. Meyer. "Fluid Filling-Media for Electrical Apparatus," *Journal I.E.E.*, Vol. 86, 1940.

C. H. Pike. "Oxidation of Transformer Oil," *Electrical Power Engineer*, June, 1946.

,, "Stone Tank Transformers," *Electrical Times*, 6th June, 1946.

J. L. Miller and J. M. Thompson. "The Surge Protection of Power Transformers," *Journal I.E.E.*, Vol. 84, 1939.

E. T. Norris. "The Moving Coil Regulator," *Journal I.E.E.*, Vol. 83, 1938.

,, "Thermal Rating of Transformers," *Journal I.E.E.*, Vol. 66, 1928.

,, "Automatic Voltage Regulation," *Electrician*, 1st February, 1946.

,, "Transformer Loading," *Electrical Review*, 31st August, 1945.

R. C. H. Richardson. "The Commissioning of Electrical Plant." (Chapman & Hall.)

S. A. Stignant and H. M. Lacey. "J. & P. Transformer Book."

H. W. Taylor and P. F. Stritzl. "Line Protection by Petersen Coils, with special reference to Conditions Prevailing in Great Britain," *Journal I.E.E.*, Vol. 82, 1938.

J. G. Wellings and R. V. Wheeler. "The Short-circuit Rating and Testing of Current-limiting Reactors," *Journal I.E.E.*, Vol. 89, 1942.

CONVERTING PLANT

RECTIFIERS

THE advantages of the mercury rectifiers are :
(1) High efficiency over whole of working range.
(2) Simple operation with minimum attention.
(3) No synchronising.
(4) Very high overload capacity and insensibility to short circuits.
(5) Negligible maintenance.
(6) Low weight and no special foundations.
(7) Almost noiseless.

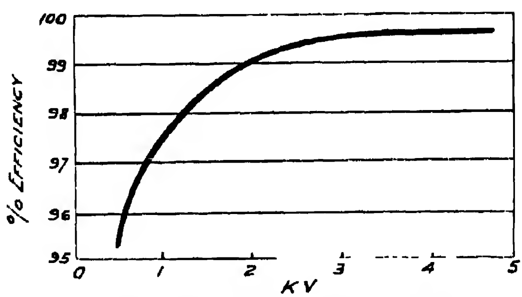


FIG. 177. Relationship between voltage and efficiency.

Rectifiers for sub-station service may be classified as :
(1) Glass-bulb mercury arc.
(2) Steel-tank mercury arc.
(3) Metal, copper oxide.

The first and second are for power supply, the third only being used for auxiliary supplies. Mercury arc rectifiers are becoming increasingly popular when A.C. to D.C. conversion is required, for they have a high efficiency, require but little maintenance, are practically noiseless, and are suited to remote and/or automatic control.

Mercury is used for the cathode as it is rapidly vaporised, ionised

and condensed and returned by gravity to the pool at the bottom of the bulb or tank without loss of material.

It is convenient to employ liquid mercury as the cathode for three very good reasons :

(1) In mercury the outer electrons are only very loosely held to the positive nucleus so that copious emission is possible at fairly low temperatures.

(2) The presence of liquid mercury means that there is an appreciable amount of mercury vapour throughout the whole envelope and this affects the operation in the following manner : electrons travelling from the cathode to the anode collide with the mercury molecules and in many cases the collision is sufficiently sharp for electrons to be split off the molecule ; these electrons will join in the stream towards the anode whilst the nucleus (or positive ion) moves towards the cathode. Now in a hard vacuum, that is one without mercury vapour in the envelope or bulb, the presence of free electrons between the cathode and the anode causes a negative space charge which limits the cathode to anode current and means that a high voltage must be applied to induce a large current. With mercury vapour, the presence of positive ion tends to neutralise this charge and only a small voltage drop of the order of 15 to 20 is required to produce very large currents from cathode to anode.

(3) A small bubble of vaporising mercury can be used in the cathode pool as the hot metal for the initial emission of electrons, an arrangement which gives almost infinite life. The hot spot is produced by starting circuits and is maintained by the heat generated owing to the bombardment of the mercury pool by the heavy positive ions. Two small auxiliary anodes operate continuously at a fixed current at all loads so that the cathode spot is maintained whatever the main load. It is permissible to have several anodes over the cathode pool since in normal circumstances current will only flow from that anode which is most positively charged, *i.e.*, is most deficient in electrons.

In a glass-bulb type the colour of the gas gives an indication of the condition ; if it is tinged with pink the bulb should be operated on excitation until normal colour is restored. The advantages of the glass-bulb over the steel-tank rectifier are :

(1) Fewer and more reliable auxiliaries.

(2) Less building space.

(3) Reduced inspection and maintenance.

(4) Makes a very flexible sub-division of units, and bulbs are easily replaced.

(5) Glass never becomes porous and the ingress of air and hydrogen are prevented, thus maintaining better vacuum.

(6) Improved insulation throughout.

(7) Simple and strong seals.

On the other hand it is claimed that the steel-tank rectifier has the advantages of :

(1) Better overcurrent characteristics.

FIG. 178. Glass-bulb rectifier (Hewittic Elec. Co.).

(2) More robust—although bulbs thought to be fragile have withstood vibration and bomb-blast in a remarkable manner.

(3) Life—glass-bulb may even last ten years or more ; steel-tank, ten years or over.

(4) The pumpless air-cooled steel-tank rectifier avoids the use of vacuum-maintaining auxiliaries.

The largest single bulb will do 500 A at 500 V, *i.e.*, 250 kW, but glass-bulb rectifier sub-stations are in service operating at 2,400 V with an output of 3,000 kW. The bulbs are arranged in group formation.

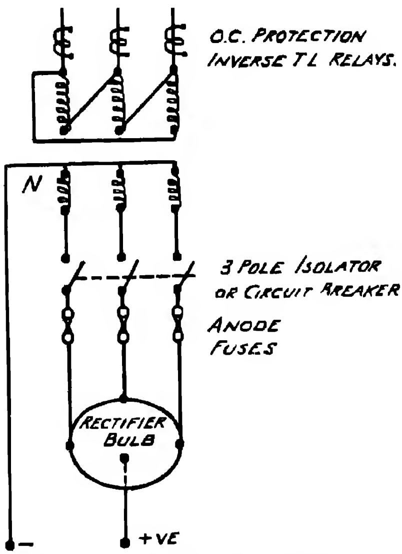


FIG. 179. Rectifier main connections.

Glass-Bulb Rectifiers. Consist of a transformer by means of which the A.C. supply to the bulb is stepped down or up to a voltage suitable for use with the bulb. A transformer may serve one or more bulbs, depending on the output desired. Each bulb and its ancillary apparatus is mounted in a sheet steel cubicle (Fig. 178), and if more than one bulb is installed per transformer a three-pole air-break isolating switch can be included to make each cubicle " dead ". A faulty bulb can be isolated without shutting down the complete bank. An anode fuse is included in each pole to afford protection. High rupturing capacity, non-expulsion fuses with renewable fusible elements give effective protection against arc backs. When one unit was hit by lightning, eleven of the twelve anode fuses blew. The capacity of the bulb type is limited by the current which can be carried—usually 700 amps., although 1,000-amp. bulbs are in service. Figs. 179 and 180 show the main electrical connections and Fig. 181 the characteristics of this type.

The sealed bulbs operate at earth potential and do not require vacuum pumps, water cooling, pressure gauges, etc. Absence of a cooling system eliminates the problems of electrolysis and inhibitors

to prevent corrosion. The operating costs are low, there are no heavy foundations, easy inspection of the bulb condition, simple replacement, and high vacuum which lasts indefinitely are particular features of

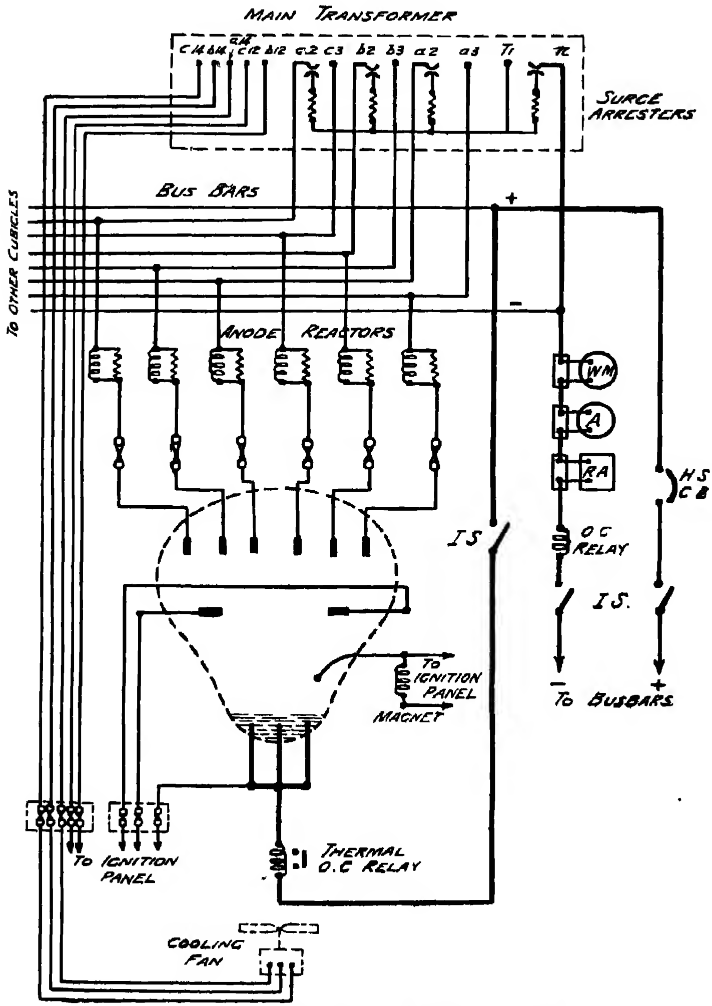


FIG. 180. Main connections, glass-bulb rectifier.

this type. Should a bulb lose its vacuum it can be returned to the makers for re-evacuation. Overloading can result in cracking of the bulbs.

Anode Inductance Coil. A three-phase anode inductance is provided, the magnetic circuit of which is divided into two parts. To vary the coil inductance non-magnetic packing is inserted between the two sections. Adjustment is necessary to balance the bulb loadings where they operate in parallel. Slight differences in length of anode arms

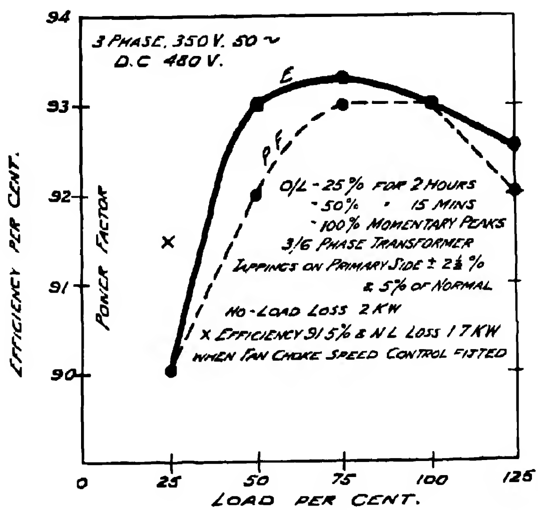


FIG. 181. Glass-bulb rectifier characteristics.

between bulbs which are to operate in parallel, or a difference in the size of condensing chamber, or even in the degree of vacuum, may result in unequal sharing of the load. Where two cubicles work in hexaphase parallel, it is usual to have one inductance core wound with two separate windings, one for each bulb. Finer adjustment is possible giving better performance, and simplifying cubicle layout.

Adjustable choke coils in series with each anode provide a means of balancing current distribution between anodes and between bulbs operating in parallel. Balancing is done during initial test operation of the units by varying the air gap in the laminated iron core of the variable reactor. Using a clip-on ammeter, fibre spacers are added to

or removed from the magnetic circuit and the currents can be balanced down to less than 10 per cent. load.

Bulbs. The bulbs are of glass, constructed for three-phase or six-phase working—having either three or six arms. The bulb is shaped so that its dome forms a space in which mercury vapour is condensed by air cooling. For best operation it is advantageous to have the anode electrodes screened from the ultra-violet rays emitted from the cathode spot and also have these electrodes away from the path of the mercury vapour rising from the cathode. Glass makes possible a shape without the need for shields. The arms carry the anodes from which cables are taken to the anode inductance windings. To obtain as small a space as possible between the cathode and the anodes, which is necessary for the valve action of the rectifier, the anode arms are bent at right angles. Such a shape prevents mercury from reaching the anodes. The bulbs are of special tough heat-resisting glass which does not melt under 1,000° C., whereas the normal working temperature is about 250° C. Glass is of practical value as observation of the arc inside the bulb during course of manufacture and inspection when in service are possible. It can be seen whether the transformer is working symmetrically. Each bulb is also fitted with an ignition electrode and two excitation electrodes. The cathode is formed by a pool of mercury at the base of the bulb, from which the D.C. positive connection is taken to the cathode-inductance coil or the positive side of the D.C. switchboard. A number of cathode stems are sealed through the bulb and make permanent contact with the mercury.

The sealing at the electrodes is effected by using a tungsten conductor which has about the same thermal coefficient of expansion as the glass and to which heat-resisting glass can be bound quite satisfactorily.

Anodes. The main anodes are of graphite, grooved to facilitate radiation of heat from them and mounted on molybdenum stems. Graphite is considered to be more suitable than iron when operating under temperature conditions of 400°–600° C. The stems are covered with glass, the coefficient of expansion of which enables it to be sealed with the metal without incurring strain. The glass-covered stems are sealed into the glass of the anode arms, which are finally sealed on to the main bulb.

Cathode. The "cathode spot" is a point of incandescence on the surface of the mercury which moves with great rapidity, and from which particles of mercury become vaporised and eject at high velocity.

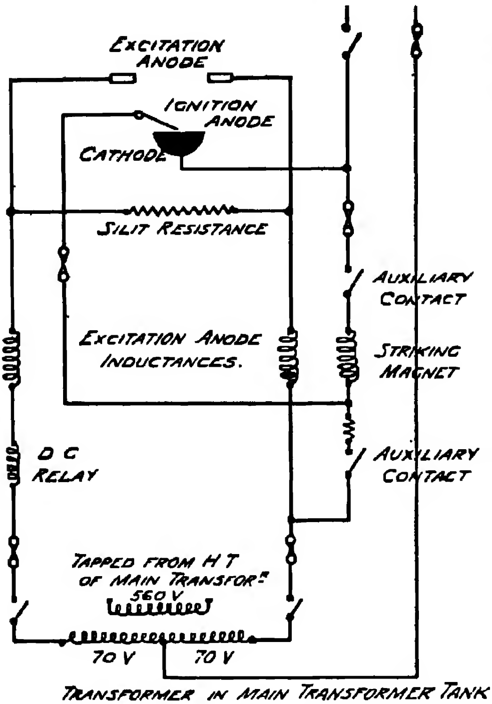


FIG. 182. Ignition and excitation circuits.

The temperature of the cathode spot is about 600° C., whilst the temperature of the luminous cloud immediately above is probably in the region of 2,000–3,000° C.

Ignition and Excitation Circuits. The ignition and excitation electrodes or anodes obtain their supply (Fig. 182) from a small winding on the main transformer, or, alternatively, a separate transformer. To start up a bulb it is necessary to bring the ignition electrode in contact with the cathode mercury pool, and the resulting small arc is sufficient to ionise the mercury vapour and allow the excitation electrodes to function. A cold bulb may require repeated ignition before adequate vapour pressure is produced for the excitation electrodes to attain stabilised operation. If normal vacuum is obtained and the excitation current is correct, the bulb should strike up as soon as the ignition arc has been drawn out. Small glass-bulbs may be started up by tilting the whole bulb and breaking and making two parts of the mercury pool. In larger units the ignition electrode is operated by way of an external solenoid. The excitation electrodes are located below the main anodes and maintain the arc should the load current fall to a low predetermined value—probably one to two amperes. It is possible to utilise the ignition electrode for excitation purposes if a D.C. supply is available, otherwise it is usual to provide a set of two, three or six excitation electrodes. These electrodes maintain sufficient current in a local

circuit to keep the cathode spot functioning. A thermal relay is included in the control circuit, to protect the bulb against sustained overloads below the setting of the circuit breakers, and also serves to protect it against overheating due to fan failure.

Heaters can be included to facilitate cold morning starting.

Cathode Inductance Coil. This coil is primarily included to facilitate load sharing of the bulbs by adjustment of the magnetic circuit in a similar manner to the anode inductance coil, and it also assists in smoothing the ripple in the D.C. circuit.

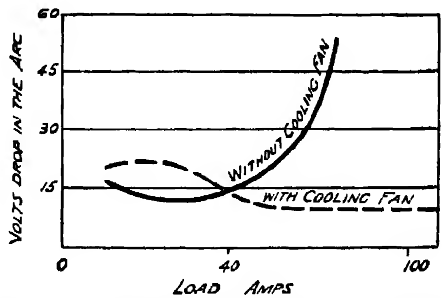


FIG. 183. Typical glass-bulb rectifier characteristics.

Cooling Fans. The effect of artificial cooling on the loading of a rectifier bulb is shown in Fig. 183. A motor-driven fan is provided for each bulb or group of bulbs and its speed is arranged to vary according to the load on the unit. A heavy-current relay is inserted in the main cathode lead to the D.C. busbars, and when the load reaches predetermined values—high and low—the relay closes or opens the fan-motor circuit. Continuous closing and opening of the circuit is prevented by setting the low load value somewhat lower than the initial operating setting. The motor is of the three-phase squirrel-cage type operating at 100 volts, the speed being varied by means of a three-phase choke in the motor leads. This choke coil is of special design, having additional windings that are connected in series with the negative connection to the main transformer neutral. At heavy loads the choke coil magnetic circuit is saturated and the choking effect on the A.C. windings is much reduced. With a reducton in choking effect (back e.m.f.) there is a higher voltage at the motor terminals with consequent increase in speed. When the load is low, the magnetic flux is reduced, and the choking effect is increased with consequent

drop in motor speed. The fan-motor circuit is therefore dependent on the induced flux in the magnetic circuit due to the load current flowing. This choke control device for regulating the speed of the fan motor according to the bulb load, effects a reduction in no-load loss and improves the overall efficiency at low load.

Both wood and steel (cast and fabricated) have been employed. The sheet-metal two-blade fan was objectionable on account of windage and noise, but the wooden propeller type has given satisfaction. The fabricated metal blades do not appear to be strong enough to withstand the rapid changes of speed. Mahogany and oak pattern blades have also been used. In some of the larger units (600 and 1,000 amp. bulbs), a fan has been fitted above and below the bulb. A considerable quantity of air is displaced by these fans, and adequate ventilation is necessary. Where outside air of a dusty nature is drawn into the building, it is desirable to include air filters in the intakes. When a bulb is operating under heavy load fan failure may cause back-fire. A back-fire does not always result in damage to the bulb, and it is often possible to re-start almost immediately on the excitation circuit.

Some 165 c.f.m. of air per kW loss at an operating ambient temperature of 30° C. is required. With a 93·5 per cent. efficiency at full load, losses on a 1,500 kW unit (4 cubicles) are 97·5 kW requiring some 16,000 c.f.m. Fans in this installation draw cooling air up through cubicle base and louvred side walls. Louvres in the building wall at the second floor level of the rectifier room and an entrance from the transformer bay which is open to the outdoors provide the cooling air required. Exhaust is by way of manually-controlled louvres in the roof of the building.

Automatic electric heater units provide protection against minimum ambient temperature specified at 6° C. Normal operating range for the equipment is 10–30° C., heating of the air below 10° C. is desirable to facilitate vaporisation of the mercury.

Arc Voltage Drop. If current-flow through the arc is not broken, a low voltage will maintain the arc, and the voltage drop across the arc for a given rectifier is almost independent of the electrical load. This voltage drop is made up of 6·5 volts at the anode, 5·5 volts at the cathode, and 0·1 volt per cm. length of arc—20 volts may be taken as an average figure. The efficiency therefore remains high at all loads.

Operational Experiences. A main lead attached to the cathode came adrift, hung down, and was subsequently driven across the

positive busbar by the fan blades, and touched the grille behind the bulb. The circuit breakers on both sides opened promptly and confined the damage to a hole burnt in the grille, a damaged cathode lead, and minor burning on the positive busbar. But for the correct setting and rapid action of the protective gear, the trouble may have been serious and costly. It appears desirable that all similar connections should have spring washers to prevent slackening. The cubicle layout would also be improved by placing the positive busbar along the top and thus eliminate similar accidental contact as that just described.

In another installation two bulbs exploded, causing damage to the auxiliary apparatus in the two cubicles, and resulted from the graphite anode falling whilst the bulbs were on load. At the time of the trouble this bank was carrying about half-load, and the automatic gear cut it out promptly and brought the standby bank into service. The origin of the trouble appears to have been a flash-over in one of the bulbs, the high rupturing capacity fuses failing to clear. Fuses should be capable of dealing adequately with the D.C. component in the circuit, for this appeared to contribute to the trouble.

A bulb was responsible for blowing several sets of anode fuses, almost one set every twenty-four hours. Auxiliary apparatus and loading were in order, but the bulb gradually lost its vacuum. The condensed mercury vapour in the bulb tended to adhere to portions of the walls of the bulb in sticky looking patches instead of running back into the cathode pool. The first trouble experienced was the blowing of one anode fuse and two excitation fuses, and the internal surface of the bulb showed a rather splintery appearance.

If a bulb loses its vacuum it is always possible to clean and re-evacuate it, as the glass is repairable. The cost of repair will depend on the condition of the bulb, and sometimes a repair can be carried out at a very small charge. If a bulb has lost its vacuum and requires to be opened, thoroughly examined to locate the fault and then be re-evacuated, treated and completed, the cost is likely to be about 50–60 per cent. of the total cost of a new bulb. A bulb so repaired will be equal to a new one in so far as service is concerned. The bulb in question was of the six-arm type and had given five years' service before this trouble occurred.

Steel-tank Rectifiers. There are two types of these : (a) water-cooled, with vacuum pump ; and (*b*) pumpless, air-cooled.

Its most significant feature is that it is generally provided with

vacuum pumps because, owing to its large size, it is not possible to make it permanently vacuum-tight. It is also difficult to arrange for adequate dissipation of heat by air-cooling, and it is therefore usually water-cooled. The characteristics of the steel tank are, therefore, large size, high capacity, but with more complicated auxiliaries.

Water-cooled Type. They are suitable for very large outputs and have proved satisfactory, but are gradually being superseded by glass-bulb and pumpless steel-tank rectifiers for certain duties and outputs.

Pumpless, Air-cooled Type. This type has all the advantages of

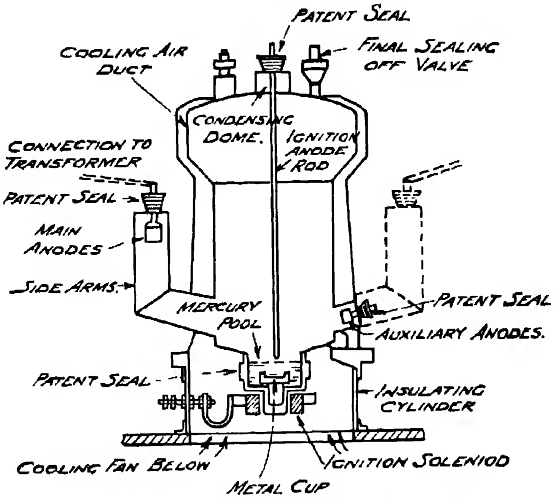


FIG. 184. Pumpless air-cooled rectifier.

the glass-bulb and steel-tank types, in that it does not require a vacuum pump, and a steel container with air-cooling is used. The sealing on the container, or tank, is done by means of a patent seal at all points of connection—anodes, etc.—and consists of a number of thin mild steel cones which are coated with special vitreous enamel. After assembly of the cones in the top and bottom members the entire pack is fused solid in an electrically-heated oven. The seal has a high dielectric strength and is capable of maintaining an absolute vacuum. A cooling fan is placed below the rectifier. The pumpless type, illustrated in Fig. 184, is made with current ratings varying from 350–850 amperes for D.C. voltages up to 800 volts. For 1,500 and 3,000 volts, rectifiers of this type are made as single units for outputs of 1,000 and

1,500 kW. The side arms are designed to serve as an anode shield for preventing arc-backs, and also act as a radiating surface for dissipating heat from the anodes. On closing the main circuit breaker the required voltage is applied and, at the same time, the ignition solenoid is energised so that the metal cup, which is above the mercury surface before ignition, submerges and the mercury trapped in the cup is brought out of contact with the ignition rod. This starts an arc, and electrons emitted from the cathode are sufficient to enable the rectifier to operate. Advantages are :

(1) No water supply or pumping equipment required.
(2) Vacuum pumps are excluded.
(3) Carries heavy over-currents.
(4) Free from back-fires.
(5) Glass is not used.

Vacuum Chamber. Is of cylindrical welded steel-plate construction, arranged to allow the mercury condensate to run to the cathode pool. This material has the advantages of facilitating manufacture, freedom from porosity, and immunity from attack by mercury. The chamber is within a shell which serves as a water jacket for cooling. The anodes are fixed on top of the tank, and the anode shields fit within the main chamber. Internal cooling is used on the larger sizes and promotes rapid condensation of the mercury vapour, thus controlling the pressure within working limits. Too great a cooling surface impairs operation and baffles surround each anode, to prevent spray from the cathode striking the anode material and producing local hot spots. A baffle formed by the flume of the main condensing chamber will also assist. The final stages in manufacture consist of subjecting the whole tank and its internal parts to a high temperature in an electrically-heated oven and simultaneously evacuating it continuously by a vacuum pumping unit. In the final electrical bakeout the rectifier is operated at low voltage and a heavy current is applied, which completes the process of removing all traces of occluded gases from the materials and interior surfaces of the rectifier. When installing a rectifier, the vacuum connections should be made off as quickly as possible to reduce leakage of air to the tank, and so minimise the time required for re-establishing good vacuum.

Cathode. The cathode mercury pool is carried in a water-jacketed steel-plate container, insulated from the vacuum chamber by an annular porcelain insulator. The cathode spot is centred by a refractory insulating cylinder of quartz or other suitable material. The

cathode is water-cooled to maintain the mercury at a reasonably low temperature. The refractory liner dipping into the mercury acts as a separator, so trapping any impurity in the mercury.

Anodes. Graphite of special grade is used and the size is governed by the current rating, allowable current density in material, density in the arc-path at overcurrent outputs, and the internal temperature. The heat generated at the anode surface is probably about 5 watts per ampere, and it is principally dissipated by radiation. With temperatures of the order of 600° C. any impurities in iron would result in local hot spots sufficient to cause fusion and, maybe, back-fire. Hence the use of special graphite.

Anode Shields. These protect the anodes from direct impingement of mercury spray from the cathode, also vapour blast. They reduce stress in the anode due to electronic bombardment at a time when the voltage wave is in the negative half-cycle, and also minimise back-fire. The anode current and tank temperature can be increased if division plates are included to sub-divide the arc-path to anode. The shield may be insulated or earthed to the tank, but if insulated the voltage attained will vary with respect to its anode voltage.

Seals. The principal types are : (1) Rubber ; (2) Mercury ; (3) Micalax ; (4) Weintraub.

Micalax is a mixture of mica and lead borate which is moulded under a high pressure and at a high temperature, and serves as the insulator in addition to forming a seal. The fourth type is made up of a number of thin mild steel cones treated with a special glass, and after assembly in the form of a seal, are electrically-heated in an oven until the unit is fused solid. The seal is bolted to the machined face of the tank. Some difficulty may be experienced in locating a faulty seal with types (1), (3) and (4).

Excitation and Ignition. The ignition electrode is of the " dipping rod " type, Figs. 185–187 suppied with A.C. or D.C. in a similar manner to the excitation electrodes. The excitation electrodes can be supplied at low voltage from a metal copper oxide rectifier, a small glass-bulb unit, an independent motor generator set, or from a generator driven by the water pump motor. The heating coil of the mercury vapour pump is connected in series with the excitation arc, which tends to stabilise the arc and reduce the no-load losses of the rectifier. If A.C. excitation is employed, two electrodes may be used single-phase, or an electrode may be placed near each main anode operating on a poly-phase system, but lagging its main anode by some 30 electrical degrees. The poly-

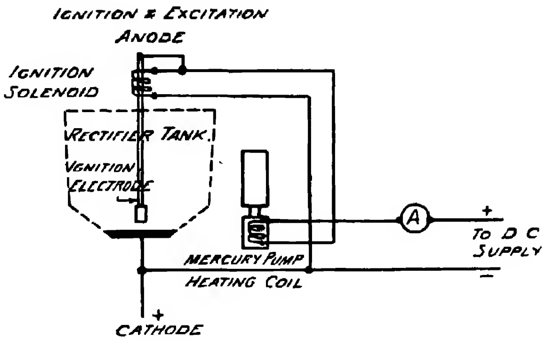


FIG. 185. Ignition and excitation circuit.

phase system is more stable, since the whole excitation ionisation is given to each main anode in turn, and in addition to this, starting up of the main anodes is improved, and better protection is afforded against back-fire. With A.C. excitation, at least one additional vacuum seal is required on the tank, together with a contactor, choke

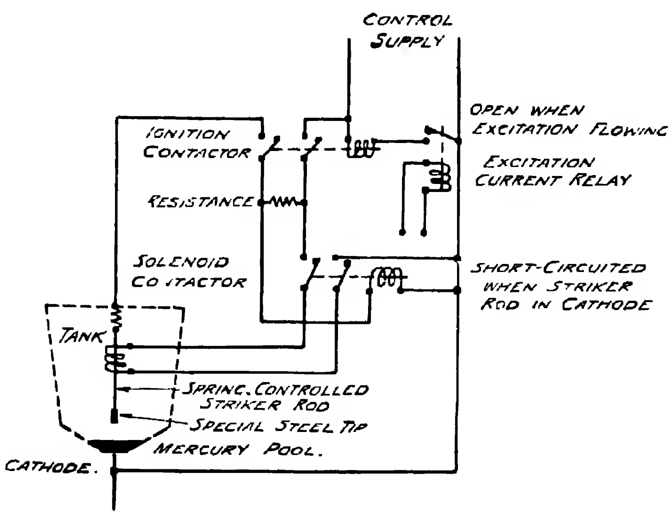


FIG. 186. Rectifier ignition circuit.

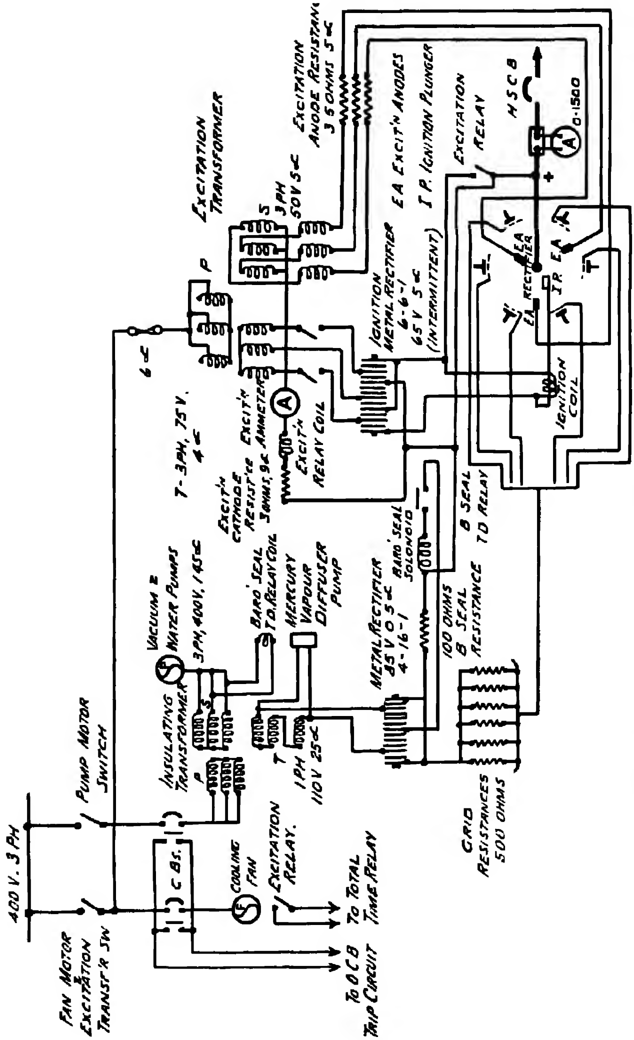


Fig. 187. Ignition, excitation and control circuits for steel tank rectifier.

coil and resistance. The excitation loss is probably in the region of 0·5–1·0 kW, and for a given circuit loss A.C. excitation can provide a

larger exciting current than D.C., since the arc can be stabilised by a series reactance in place of a series resistance.

Mercury Vapour and Exhauster Pumps. Two pumps operate in series (Fig. 188), the first being of the ejector type and the second a rotary exhauster. In the ejector type, mercury is boiled by means of a small electric induction heater, and the vapour produced issues through one or more jets to extract and trap the air. An ordinary resistance heater is unsuitable for boiling the mercury, as the resulting temperature of the heater element would be near its safe limit after allowing for heat drop in the air space and the insulation. The rotary vacuum

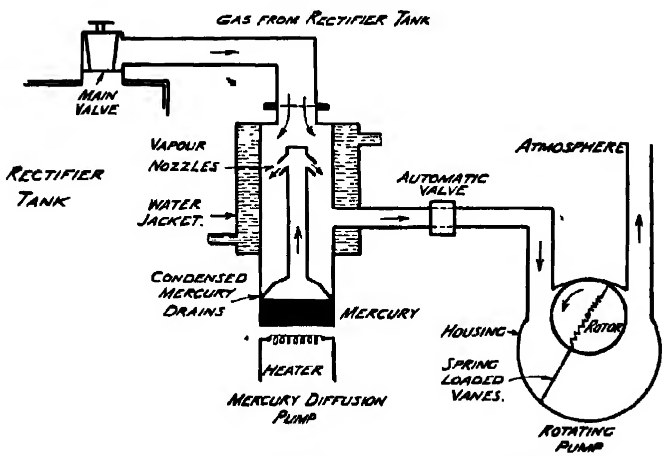


FIG. 188. Two-stage vacuum pumping system.

pump or exhauster, which operates in series with the diffusion pump or ejector, exhausts to the atmosphere. The rotary pump absorbs about 0·2–0·4 kW.

Intermediate Vacuum Chamber. This is placed between the mercury diffuser pump and the exhauster, and permits of the latter being shut down for certain conditions of operation of the rectifier, although the general practice is to run both pumps continuously even with the rectifier shut down.

McLeod Vacuum Gauge. Referring to Fig. 189, the mercury, M, is able to rise in the tube, T, and causes the gas trapped in the bulb, B, to be compressed, so that if its volume is reduced to V, it will be necessary to have a head of mercury, H, to hold it there. With a perfect

gas in the bulb, the original pressure in microns is then equal to the head, H, in m.m. divided by the ratio of compression multiplied by 1,000. This gauge is simple and reliable, since the calibration is fixed by the constant dimensions of the instrument. Its disadvantage is that it has to be manually operated, and is therefore not adaptable to automatic indication of the rectifier vacuum.

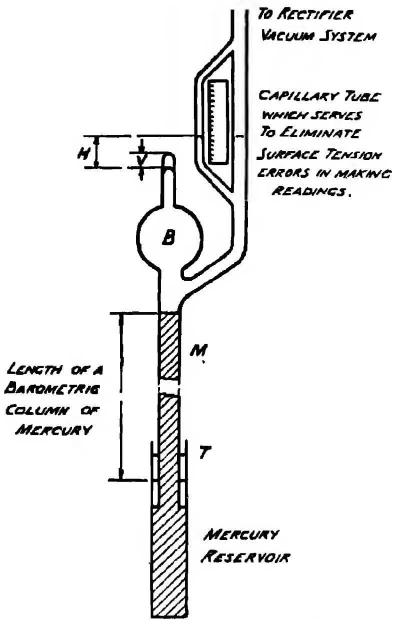


Fig. 189. Principle of McLeod vacuum gauge.

Pirani Vacuum Gauge. If a foreign gas is present in the rectifier tank it lowers the temperature of the filament in the valve, which in turn upsets the balance of the bridge (Figs. 190 and 191). This gauge is used to operate a vacuum relay when the tank pressure has increased (say, from 6 up to 20 microns, depending on the type of rectifier) and disconnects the rectifier from the busbars. When the pumps re-establish normal vacuum conditions (2 to 5 microns) the rectifier is released for a restart. (1 micron = 0·001 m.m. of mercury.) The compensator and gauge filaments are made of platinum, and have similar resistance values. The gauge filament is exposed to rectifier vacuum and its loss of heat; therefore its resistance varies according to vacuum conditions. The equipment is very sensitive, and small changes of vacuum put the bridge out of balance and cause a current to flow through the meter and sensitive relay.

Water-cooling Systems. Two cooling systems are employed (Fig. 192)—one for the rectifier and the other for the mercury vapour pump—by reason of the fact that the temperatures and the periods of operation of rectifier and pump differ. The rectifier tank is not at earth potential, while the cathode, which is also water-cooled, is at the potential of the D.C. busbars. The cooling system therefore has to be arranged so

that the rectifier tank is maintained at its potential above earth, and the cathode insulated. The supply pipework is insulated from the rectifier by including a length of rubber tubing. The length of the tubing will

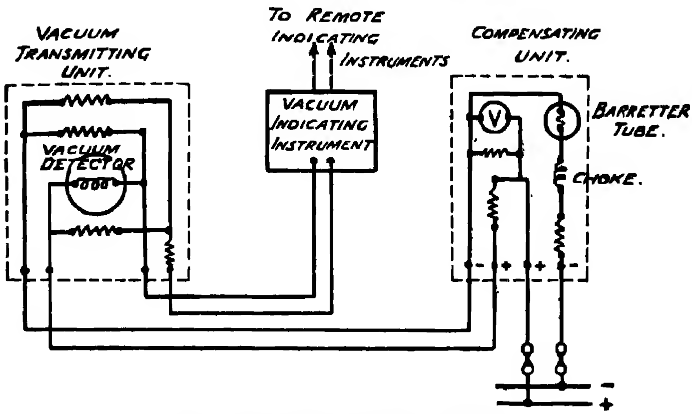


FIG. 190. Pirani connection diagram.

depend on the purity of the water (pure water is a good insulator), and also on the sectional area of the water column needed to give the desired

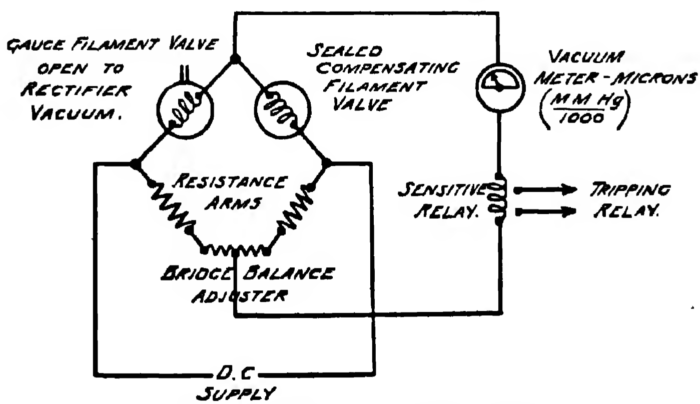


FIG. 191. Loss of vacuum protection (Pirani).

flow. A 10-ft. length is usually sufficient for medium voltage rectifiers. The leakage is a few milliamps, and electrolytic corrosion at the junction of the pipe system and the rubber tubing is small. Non-corroding bushes may be used. Town's water is not a perfect insulator, and

leakage current may cause electrolysis to take place, and the free oxygen will combine with the iron to form iron-oxide, or if a chlorine is present in the water, this will separate to combine with the iron to make chlorine of iron. Length of rubber tubing required is usually :

10–15 ft. up to 600 volts, depending on ohmic resistance and chemical composition of water.

75 ft. or more for 1,500 volts and over—in which case the tubing is coiled on an insulated frame and kept within the enclosure.

The temperature of the rectifier is controlled by thermostat-oper-

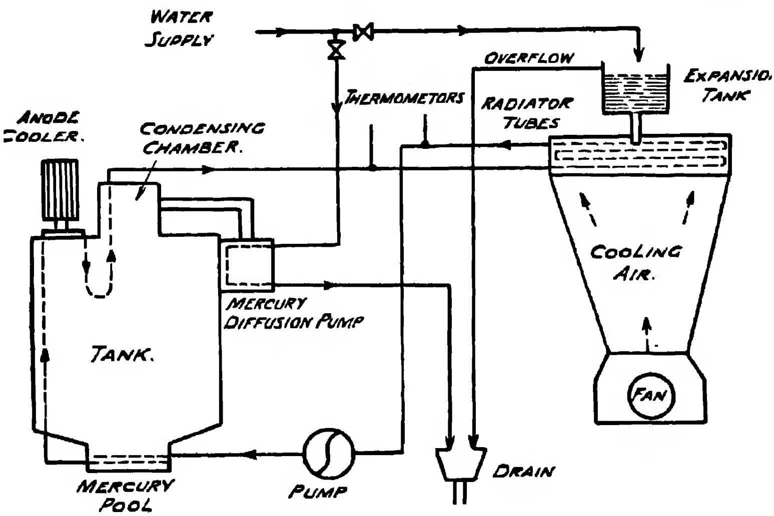


FIG. 192. Rectifier cooling system.

ated water valve, regulating the flow to maintain a constant outlet temperature. Cooling water is taken from town's main or other convenient source of supply, and re-circulating systems are usual. The re-cooler should be positioned so that its end-covers can be removed and the tubes cleaned. The storage tank should have a settling chamber and the supply to the high vacuum pump should pass through a mud trap. The cooler is usually mounted on insulators, so that the potential with respect to earth is the same as the rectifier tank, thereby eliminating electrolytic action. The air blower and motor are at earth potential, and air is supplied to the cooler through trunking which has an insulated section fitted below the cooler.

With a closed system failure of water supply does not entail inter-

ruption and water conditions can be maintained which reduces maintenance on water jackets. The rectifier tank and everything in electrical connection with it, including the apparatus on the secondary side of the ignition and excitation transformer, have a potential approaching that of the cathode, and care should therefore be taken to ensure that any earthed metal does not come in contact with either the equipment or the pipework connected thereto.

Smoothing Circuits. These are necessary with all rectifiers if harmonics in the D.C. system are likely to cause interference with telephone circuits. The R.M.S. values of the harmonics are given in Table 17.

TABLE 17. *Harmonics in Rectifier Circuits*

Frequency of the harmonics in rectified current Cycles	Number of transformer secondary phases			
	2	3	6	12
2 × 50 = 100	42 2			
3 „ „ = 150		17·7		
4 „ „ = 200	9·44			
6 „ „ = 300	4·05	4·05	4 05	
8 „ „ = 400	2·25			
9 „ „ = 450		1·77		
10 „ „ = 500	1·43			
12 „ „ = 600	0·99	0·99	0·99	0·99
14 „ „ = 700	0·73			
15 „ „ = 750		0·63		
16 „ „ = 800	0 56			
18 „ „ = 900	0·44	0·44	0·44	
20 „ „ = 1,000	0·36			
21 „ „ = 1,050		0·32		
22 „ „ = 1,100	0·29			
24 „ „ = 1,200	0·25	0·25	0·25	0·25
Resultant Total Percentage Ripple	61·50	25·8	5·8	1·4

Fundamental frequency = 50.

The frequency of harmonics are multiples of both the periodicity of the A.C. supply and also the number of phases used in the secondary of the rectifier transformer. The harmonics below 1,200 cycles are likely to cause trouble (the twenty-fourth in a 50-cycle system). The resultant ripple is given, and the need for a smoothing circuit in six-phase rectifiers is apparent, whereas such a circuit is not nearly so essential in twelve-phase rectifiers. The figures are based on the assumption that the A.C. supply to the rectifier transformer has a wave form free from harmonics. Tuned resonant shunts (Fig. 193), serve as by-passes for harmonics, and the D.C. reactor limits the

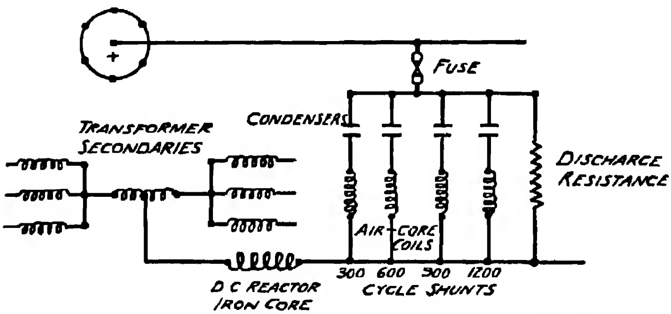


FIG. 193. Typical tuning circuit for a 50-cycle rectifier.

harmonic current. The tuned portion shunts it from the load circuit, and the harmonic therein $= \dfrac{\text{Impedance of Shunt Circuit}}{\text{Impedance of Reactor}}$, the value of which is about one-sixth to one-tenth of the original value. The condensers are so designed that slight variations of supply frequency do not affect the tuned circuits. The D.C. reactor may be of the air core or iron core type, and the flux density in the latter should be sufficiently low to prevent saturation when heavy currents are flowing. One set of tuning circuits may be installed for each sub-station, but a separate unit is usual for each large steel-tank rectifier.

Interference to telephone circuits is possible where rectifiers supply a traction load with overhead lines or the third rail running near and parallel to the telephone lines. The inductive loop of the power circuit is large, and being completed through earth any inequality in the insulation resistance to earth of the near-by telephone lines renders them more liable to inductive effects from the power circuits. Ripples with peaky wave form may result from parallel operation of sub-

stations not having tuned circuits. In some cases it may be necessary to separate sub-stations on the D.C. side and allocate feeders to definite sections of the system.

The D.C. reactor is bolted to the floor and all cables thereto are securely cleated. Metalwork, which may be affected by the strong magnetic fields from the reactor, should also be secured to prevent movement. The resistance of the cables should be to specification and the cables should be run non-inductively. Armoured cables, or cables in steel conduits, are not recommended, unless the magnetic circuit is made common to avoid a current flowing in the covering due to induction. The coils of the shunt should be kept apart and well clear of any building or other steelwork. The condensers and connections should be discharged before working on them. Over-loading of the shunts caused by a drop in supply frequency may result in a fuse blowing.

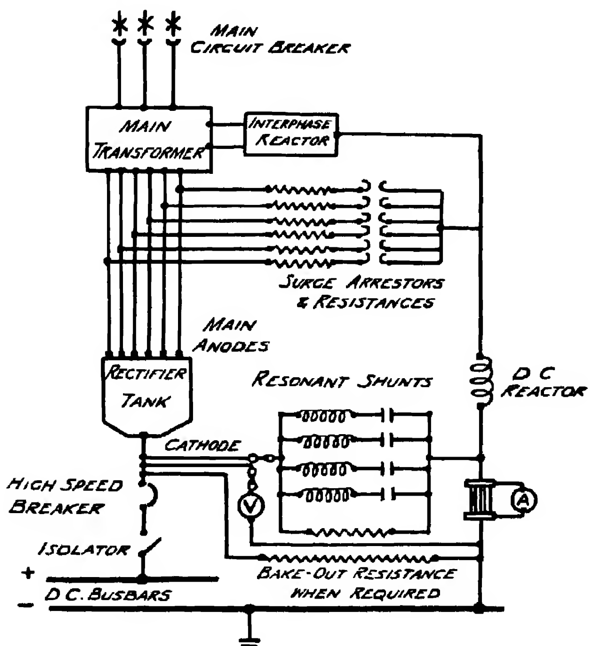


FIG. 194. Main connections, steel-tank rectifier.

Surge Protection. In starting a rectifier from cold (glass-bulb or steel-tank), with the mercury vapour pressure low, the normal balance between the ions and the electrons in the arc stream may be upset if the load current exceeds the critical value. Under such conditions, violent high-voltage surges may be set up across the arc, which may result in back-fire. These surges appear at the transformer secondary terminals, and may cause breakdown at the end turns of the windings. The transformer windings should be designed to withstand these voltage surges. Surge effects are reduced by including surge gap arrestors with a resistance across the secondary windings (Fig. 194). The connections should be run non-inductively, and if cable is used it should have good insulation and be of higher value than that used for anode cables.

High-speed Circuit Breakers. A reverse current high-speed circuit breaker is provided for the rectifier, and forward tripping high-speed breakers may be provided on the outgoing feeders. The outgoing feeder breakers may be of the latched or solenoid holding types, and where overcurrent tripping is fitted operation would be the same for either forward or reverse current. This also applies to impulse tripping. The high-speed breakers are held closed by a holding coil, and operation is by de-magnetising effect of a bucking coil or bar. This can only take place for a given polarity of holding and bucking coils, and in some installations is only arranged for forward tripping with a current at about 100 per cent. overload. Tripping by reverse current is obtained by including a polarised relay, and, in addition, there is overcurrent protection, to guard against sustained overloads of values lower than the setting giving direct operation of the high-speed circuit breaker. This is afforded by a relay with or without a short delay, one relay combining the functions of reverse and forward overcurrent protection. Where forward tripping is not provided on the high-speed breaker (rectifier or convertor), protection may be included on the higher voltage side of the transformer by a double purpose relay having inverse and instantaneous tripping. Rectifiers are installed which have latched type breakers, and no trouble has been experienced. The A.C. overcurrent relay protects the rectifier and transformer against severe forward currents. These breakers may be mounted on separate panels, or in sectionalised stone cubicles. Earthed metal should be kept at specified distances from the arc chutes. Part of the framework is at line potential and screens must be provided to prevent danger. The rectifier breaker has an interlock to trip the

main A.C. breaker in the event of back-fire, and another interlock to trip the rectifier breaker should the main A.C. breaker open. This precaution ensures complete isolation of the rectifier. If the rectifier equipment includes a rotary balancer, the switches controlling the set should be interlocked with the high-speed (rectifier) breaker, to disconnect the balancer and rectifier simultaneously.

Supplies for auxiliaries. The lower voltage supplies for auxiliaries and protective circuits may be obtained from :

(1) A separate auxiliary transformer.

(2) An auxiliary winding on rectifier transformer.

(3) A D.C. supply from : (*a*) D.C. network.
(*b*) Main rectifier.
(*c*) Battery.
(*d*) Motor generator.

If D.C. is obtained from the rectifier, the control wiring is at the same high potential to earth.

Earthing. Protection of the lower voltage (D.C.) system against contact with the higher voltage system (A.C.), may be afforded by one of the following :

(1) Solidly earthing some point on the lower voltage system.

(2) Using an earth shield between the primary and secondary windings of the rectifier transformer.

(3) Providing a static earthing device, which connects the lower voltage side of the transformer to earth should a breakdown occur between the higher and lower voltage windings of a rotary convertor transformer.

Such protection is necessary to meet the requirements of Regulation 20 of the Home Office Regulations.

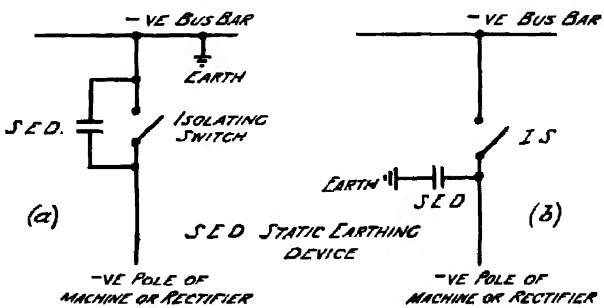


FIG. 195. Static earthing devices on traction systems.

The arrangement shown on Fig. 195 (*a*) is used for rotary convertors and rectifiers, and is only effective for the purpose for which intended if the negative busbar can be regarded as solidly earthed. The traction system may be earthed at one central point (by cable from earth plate at main sub-station to rail system at convenient centre), no part of the negative system being isolated except for testing.

In the alternative method (Fig. 195 (*b*)), the static earthing device is permanently connected between the machine or rectifier negative pole and earth. This obviates earthing the negative busbar. Such static earthing devices are not required for motor convertors, since the higher voltage windings are shielded by earthed metal. The type of earthing device fitted, when having a single paper disc, breaks down at about 750 volts.

Rectifier Ratings. For commercial and industrial service, heavy momentary overloads are infrequent, but sustained overloads are likely to be met. For traction work, momentary overloads of some high order are quite common.

Industrial service . .	25	per cent.	O/L	for	two hours.
	50	,,	,,	,,	,,	fifteen minutes.
	100	,,	,,	,,	,,	fifteen seconds.
Traction (railway service) .	50	,,	,,	,,	,,	one hour.
	200	,,	,,	,,	,,	momentarily.

The latter being carried for a time interval of five seconds with safety.

Back-fires. Back-firing or the flow of current opposite to the normal between anode and cathode is the phenomenon which limits the rating of mercury arc rectifiers. The chances of a back-fire occurring increase as the load increases and as the voltage increases, both of which tend to increase the temperature and the vapour pressure of the mercury. At D.C. voltages of less than 200 V, back-fires are rare and rectifiers can be loaded largely on the basis of reasonable heating. At higher voltages, the risk of back-fire is always present above a certain load, and for that reason the current rating is reduced as the voltage is increased, and a further reduction is also made when heavy loads are likely to be continuous for very long periods. A back-fire is essentially the sudden and permanent short circuiting of at least one anode to the cathode. This results in a short circuit between one phase and neutral of the rectifier transformer ; the healthy anodes continue to rectify and any rectifiers operating in parallel with, and motor load fed by, the rectifier, can supply D.C. through the system between the back-firing anode and the

TABLE 18. *Rectifier Data.*

Figure 196	Transformer connections		Anode current factor	Primary kVA / kW	Secondary kVA / kW	Interphase reactor kVA / kW	D.C. on load voltage factor	D.C. off load voltage factor	D.C. off load voltage rise, per cent.	Transformer winding utility factor
	Primary	Secondary								
a	Delta	Star	0·577	1·505	1·505	—	1·17 E	—	—	0·664
b	Star or Delta	3-phase Zig-zag	0·577	1·225	1·73	—	1·17 E	—	—	0·678
c	Delta	6-phase Star	0·408	1·28	1·81	—	1·35 E	—	—	0·645
d	Star or Delta	Double 3-phase	0·289	1·05	1·48	0·085	1·17 E	1·35 E	15	0·741
e	,,	Triple 3-phase	0·408	1·05	1·79	—	1·35 E	—	—	0·704
f	,,	Quadruple Zig-zag	0·144	1·01	1·65	0·09	1·17 E	1·4 E	20	0·704
g	Delta	Triple 4-phase	0·167	1·02	1·61	0·035	1·27 E	1·4 E	10	0·741
h	Series, Star, Delta	Double Triple phase	0·173	1·03	1·67	—	1·4 E	—	—	0·741

E=R.M.S. Anode voltage.

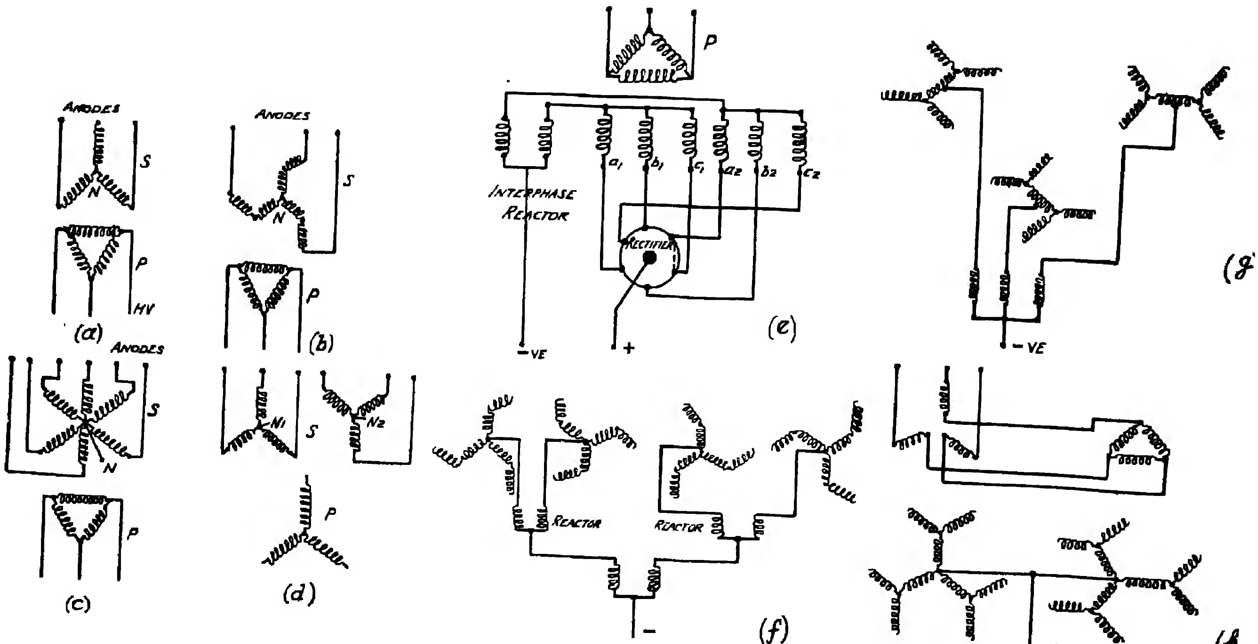


FIG. 196. Rectifier (*a-h*) transformer connections.

star point. The tendency of a rectifier to back-fire depends on the control of the vacuum and the vapour pressure obtained in the bulb or tank. Should the anodes become overheated and reach a temperature which interferes with electronic emission, then a flash-over or back-fire may occur. A back-fire occurs when the gas insulation against the inverse voltage fails and when this takes place current can flow directly between two or more anodes, virtually causing a short circuit across the transformer windings connected to them.

Repeated back-fires were experienced with a 900 kW steel tank unit and the symptoms present were : operation of D.C. reverse current and H.V. overcurrent relays and a rise in pressure of a few microns. Polarity indicators were placed on the anode leads and by checking them after the occurrence of back-fires on four occasions it was established that the same anode was giving trouble. On opening out it was found that the surface of the anode porcelain supporting insulators were damaged at the bottom ends. These are in contact with a steel ring which is screwed on the anode support between the graphite anode and the insulator.

Cables and Connections. Anode cables should be insulated to withstand 2·5 kV for medium voltage rectifiers, and 5 kV for traction rectifiers of 1·5 kV operating voltage. Taped copper connections may be used instead of cables from the transformer secondary to the anodes. From Table 18 it will be noted that the cable sectional area on the secondary sides of the transformer are not in strict ratio as in ordinary power transformers. Take, for example, a 25 kW two-wire 230-volt rectifier. The best form of transformer connection is delta three-phase zig-zag, anode factor 0·577 ; current $= \frac{25 \,.\, 1{,}000}{230} \,.\, 0{\cdot}577$ $= 62{\cdot}5$ amps. per phase, though R.M.S. value of the anode voltage to neutral is only $\frac{\text{D.C. volts}}{1{\cdot}17} = 196$ volts. On the H.V. side the primary kVA is given in Column 5 as 1·225 times the kW rating of rectifier ; therefore the actual kVA in this example $= 1{\cdot}225 \times 25 = 30{\cdot}4$.

$$\text{Current I} = \frac{\text{kVA}}{\sqrt{3}\text{V}} \text{ where V} = \text{ primary voltage between phases.}$$

Cables and taped connections (Figs. 197 and 198) for the anodes should be firmly secured to prevent distortion due to electro-magnetic forces under short-circuit conditions. The creepage distance over the

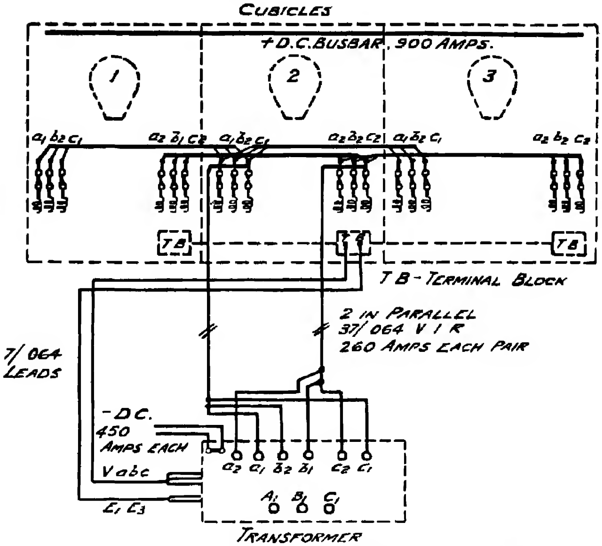


FIG. 197. Cabling for 3–167 kW glass-bulb rectifiers.

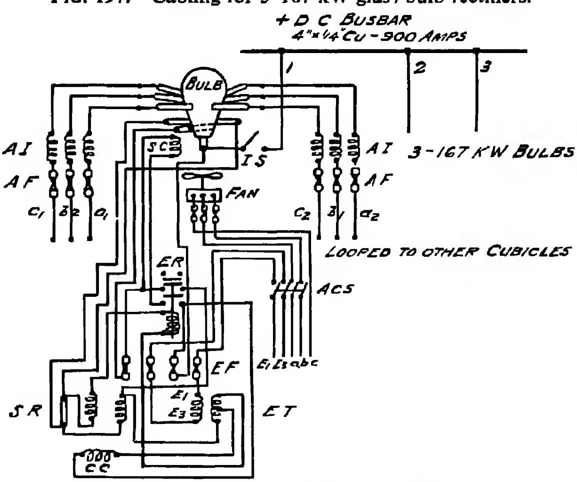


FIG. 198. Glass-bulb rectifier connections.

S.C.—Starting coil.	*E.F.*—Exciter fuses.
I.S.—D.C. isolation switch.	*E.T.*—Exciter transformer.
A.F.—Anode fuses.	*E.I.*—Exciter inductances.
A.I.—Anode inductances.	*S.R.*—Silit resistance.
E.R.—Exciter relay.	*C.C.*—Cathode choke.

insulation at the terminals of cables should be sufficient to withstand the higher voltage set up under short-circuit conditions. Cables for connection to surge arrestors should have insulation well above that for normal voltage. Voltage drop tests across joints will indicate the electrical conductivity of heavy current connections. Wiring connected to apparatus on the rectifier should be insulated to the same voltage grade as for anode cables. Small wiring carrying D.C. should be arranged to eliminate mutual induction effects.

For connections between the transformer and the rectifier, insulating bushings are provided for bare or cambric-insulated leads ; if lead-covered cables are required special six-pole cable sealing boxes are available, for anode currents up to 400 A.

Operational Experiences. A rectifier transformer developed a fault to earth some two hours after a very heavy back-fire. The transformer was isolated and tested " infinity " on both L.V. and H.V. windings to earth. The fault took almost two minutes to build up and flash-over when the earth signal bell on the H.V. side of the system operated. Back-firing was quite frequent on one rectifier, and one feature which was thought to contribute to this trouble was mercury carried over from the high vacuum (diffusion) pump into the rectifier tank. In due course this pump had little mercury in its boiler, reducing its efficiency and resulting in conditions conducive to back-firing. The connection between the rectifier tank and the pump encouraged the passage of mercury, and the heating element in the mercury boiler appeared to be much in excess of requirements. More mercury appeared to be vaporised by the heater than could be condensed by the cooler. The vaporised mercury from the boiler should all be condensed and returned to the pump boiler instead of being carried over to the tank. The loss of mercury may also have been due to the cooling water being shut off simultaneously with the rectifier, the residual heat in the heater vaporising the mercury and causing it to be drawn into the rectifier tank. This can be obviated by allowing the diffusion pump cooling water to circulate for some time after the rectifier is shut down. A surplus of mercury in the diffusion pump boiler is indicative of inefficiency in the main tank cooling system.

Trouble was experienced with a static earthing device when there was a discharge to earth during a thunderstorm from the rectifier negative, the connection being taken from the inter-phase transformer. The static earthing device (Zed type fuse) was damaged. A new static earthing device was put across the negative isolator, and also a Metro-

politan-Vickers type M.P. surge arrestor between the negative busbar and earth.

Mercury seal gauges have given false indication of levels, in that the seals have appeared to contain a full quantity of mercury, but on tapping the seal mounting the mercury disappeared. This may be caused by a thin film of mercury adhering to the inside of the glass. The levels, or floating indicators, should always be checked to make sure that the reading given in the glass is correct.

A rectifier failed to excite when an attempt was made to put it on load. On testing, it was found that an open circuit existed between the ignition electrode and cathode, with the ignition coil energised. On testing with a " Megger " between the ignition electrode and cathode " kicks " were observed which indicated that the ignition electrode was intact and in contact with the surface of the cathode pool. An accumulation of dirt on the mercury pool caused this. The rectifier tank was opened out for cleaning.

Rectifier Faults. Generally speaking, faults may be enumerated as follows :

Ignition and excitation failures—caused by poor vacuum conditions, low temperatures, defective electrical circuits, ignition rod tip breaking off or failing to make contact.

Partial loss of vacuum—defective pumps, faulty valves, seals or pipe joints.

Overheating—defective water circuit, pumps, valves, etc.

Inadvertent tripping—heavy loading before normal working temperatures obtain ; may cause back-fire and shut down the rectifier due to overcurrent. Back-fire or arc-back may also be due to continuous overloading with consequent heating of anodes ; misplaced arc shields ; defective anodes ; cracked anode insulators ; inadequate ventilation and short circuits.

Failure to maintain an arc under no-load conditions is usually due to defective excitation. Fluctuating rectifier voltage may result from unstable excitation and can be remedied by increasing the air gap of exciter choke thereby increasing the excitation current.

Blowing of anode fuses is sometimes experienced. The general effect of (three-phase) opening one-phase of the anode supply is : to reduce the average value of the D.C. output voltage, distort the D.C. voltage and current wave-forms ; disturb the balance of currents in the transformer and increase the asymmetry of the magnetic flux ; increase the D.C. ripple ; reduce the power factor ; overall efficiency

and output ; lead to intermittent arc and the probability of its failure on light load. There appears to be the necessity of affording protection against such failure of anode supply from whatever cause.

Thermostats, vacuum relays, and overcurrent relays, may also give trouble.

Grid Control of Rectifiers. The mercury-arc rectifier is an A.C. to D.C. convertor (Fig. 199) having a fixed D.C. output voltage, which is dependent on the value of the A.C. input voltage and can only be varied by external means. The inclusion of grid control enables the rectifier D.C. output voltage to be varied over an almost infinite range and opens up the possibilities of frequency changing, inverted operation, and the production of high-frequency currents. Protection against

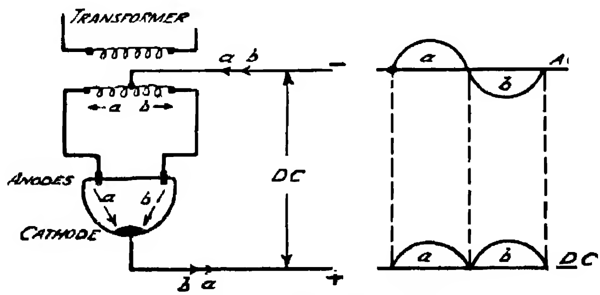


FIG. 199. Principle of rectification.

short circuits and back-fires can also be afforded, together with the advantage of breaking heavy currents by the arc. This relieves the strain on switchgear and connections, and does not give rise to transient surges as in the case of mechanical breaking of heavy currents. When a negatively charged grid is placed between the anode and the cathode it prevents the arc from striking. As soon as the grid becomes positively charged the arc will strike, and once the arc has struck, the grid has no control over it. Grids placed just below the anode can, therefore, be used for controlling the point of striking. In this way average output voltage of a rectifier can be reduced. This is reflected on the primary of the main transformer by a reduction in the power factor.

There are two principal types of grids in use : an open mesh metal basket which surrounds the anode, and a flat perforated plate screen which is placed under the anode in the path of the arc. The former is generally fitted to the glass-bulb rectifier, and the latter to the steel-tank rectifier, which has larger anodes and arc shields. The grids and

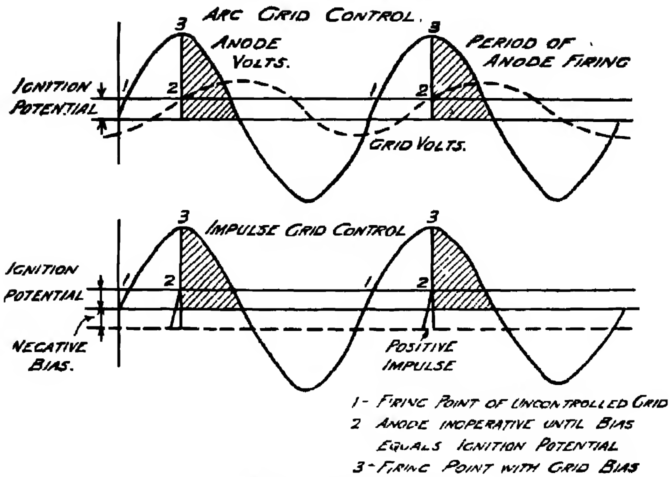


FIG. 200. Rectifier grid control.

their connections are isolated from the anodes and taken from the tank in a similar manner to the anodes. There are, broadly, two methods of grid control :

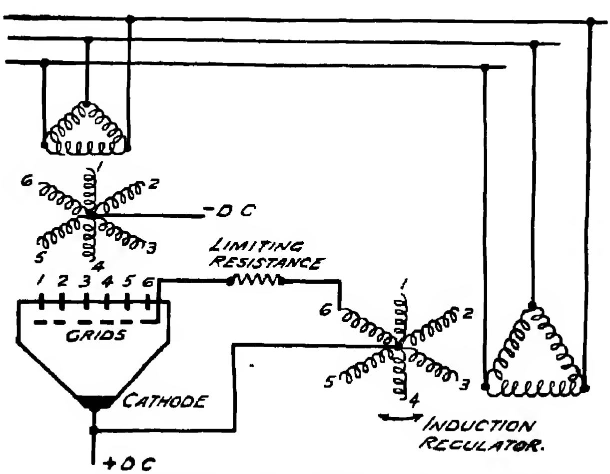


FIG. 201. Rectifier induction regulator grid control circuit.

(1) Systems using a gradual and varying grid voltage.

(2) Systems using an instantaneous or impulse grid voltage.

The first of these systems necessitates the application of A.C. voltage to the grid of the same frequency as the anode voltage, but can be shifted in phase to the anode voltage. It is a simple method and easy to apply, but its accuracy of operation is dependent on the ignition potential (minimum potential between anode and cathode to cause arc to strike) of the rectifier. The second method has the advantage of precision, for it is unaffected by ignition potential variation. The principle is that all anodes are made inoperative by a

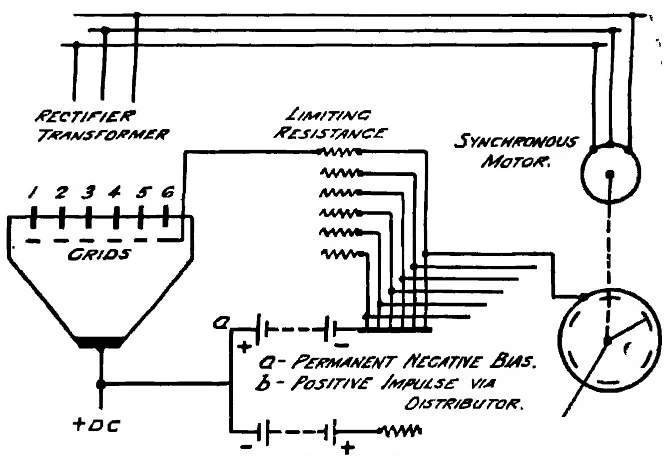


FIG. 202. Rectifier impulse grid control.

permanent negative grid bias until freed by a positive impulse potential. Fig. 200 shows the application of grid bias. An uncontrolled bias would commence to fire at 1 in the A.C. cycle, *i.e.*, when the anode voltage reaches the ignition potential. With a grid potential applied, the firing point is delayed to 3, which corresponds to the instant at which the grid potential is positive and the same value as the ignition potential 2. In the impulse system the permanent negative grid bias would prevent the anode firing at 1, and it is inoperative until the positive impulse is applied at 2. A variation in the value of the ignition potential in the impulse system has a negligible effect on the position of point 2.

Two ways of applying grid control are by induction regulator and synchronous motor distributor, the general application of which will

be seen from Figs. 201 and 202. Fault protection and inverted control is obtained as shown in Figs. 203 and 204 respectively.

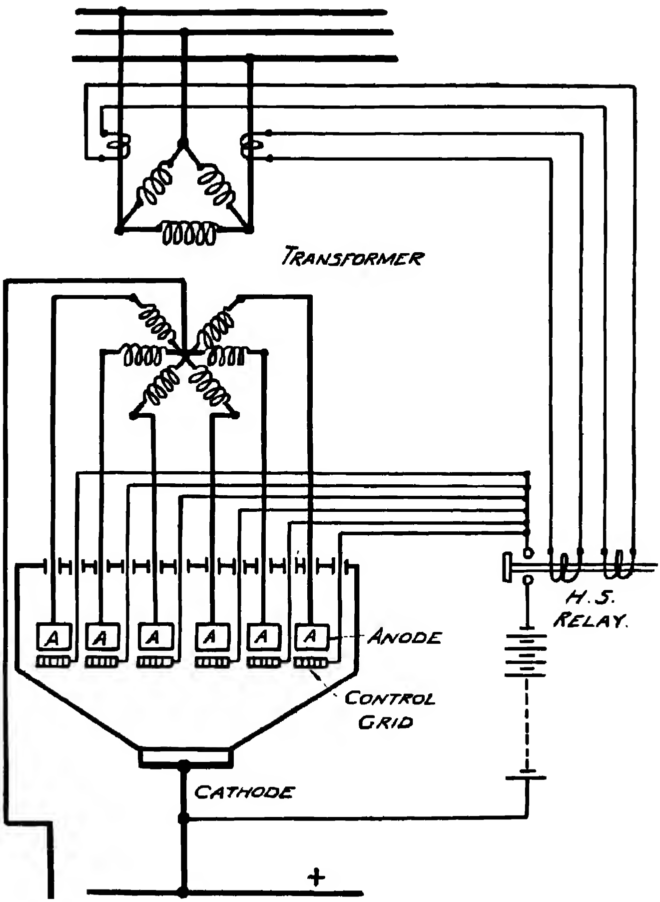


FIG. 203. Rectifier control grid fault protection.

Special Features of Rectifiers. Apart from the question of capital cost, which is in its favour, the rectifier also possesses the following advantages :

(1) Higher efficiency is maintained over a greater range of loads.

(2) It is able to deal adequately with overloads.

These are two most important factors on traction systems.

(3) Simplicity of operation ; no synchronising ; practically no delay in re-connecting to the system, thus permitting the use of simpler automatic equipment.

(4) Reliable ; being less liable to system disturbances, especially H.V. surges, than rotary plant.

(5) Noiseless ; an important feature in congested and residential areas.

(6) Low maintenance ; the auxiliaries require but little attention.

(7) Regulation controlled by tap-changing on transformer. For traction, where close regulation is not essential, control is not required.

(8) Lower building and foundation costs.

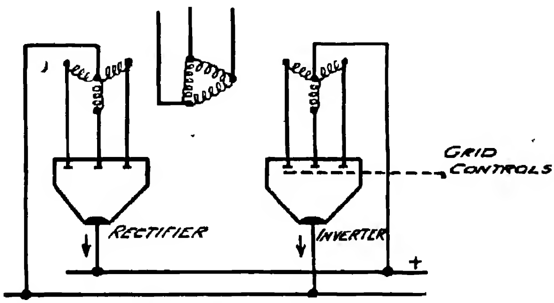


FIG. 204. Rectifier inverter connections.

Mercury arc rectifiers can operate in parallel with rotating plant, both in the same sub-station and through the feeders. The voltage characteristic almost follows a straight line, the principal drop being that of the transformer. A peculiar characteristic common to all arc rectifiers is the increase in voltage at no-load, amounting to some 15 per cent., which is reduced to normal with a load of about 5 per cent. and presents no difficulties in practice.

Metal Rectifiers. The valve action of a junction of copper and copper oxide can be used for rectification purposes. Rectifiers for different ratings of voltage and current can be obtained by assembling sufficient metal and oxide discs in series or parallel groups. The use of three-phase rectifier circuits improves the D.C. voltage wave. The open-circuit voltage is higher than the load value due to the resistance drop, and measurements should always be taken when on load. The polarity of rectifier units can be checked by a battery and galvo, but a "Megger" should not be used, as the high voltage may cause damage.

These rectifiers have many useful applications in sub-station work, such as : battery charging, control circuit, field excitation, contactor coil supplies, and inductive circuit discharge units.

Ignitron. This is similar to the steel-tank rectifier but has only one anode per cathode pool. The anode is set close to the cathode pool and each individual tank is excited at the moment when the anode becomes positive relative to the cathode. This design shows certain theoretical advantages over the more conventional arrangement, but the equipment necessary to produce repeated excitation—approximately fifty times every second—is elaborate and difficult to make completely reliable. The short anode and cathode path makes for a low arc voltage drop. It may or may not have pumps and water-cooling equipment and has been used fairly extensively for electro-chemical works where currents of the order of 10,000 amps. are necessary. The ignitron tends to show a higher efficiency due to the low arc drop, but it would appear that at continuous heavy loading it is somewhat less reliable and developments to improve the reliability have also increased the arc drop.

Trolley-bus Sub-station. Fig. 205 illustrates a rectifier sub-station for giving supply to trolley bus feeders. A fault on a cable, transformer or rectifier will shut down only one half of the plant ; the overload capacity of the remainder will enable the load to be carried until the faulty item has been replaced or both sections coupled to the second feeder. The idea is to prevent even a temporary interruption of supply and bunching of vehicles. On the D.C. side both pairs of rectifiers feed on to a common busbar, to which are connected track feeders. Each pair of bulbs is protected by a circuit breaker on the positive busbar, and a contactor on the negative. By opening the circuit breaker on the A.C. side, and the circuit breaker on the D.C., the half-unit in the sub-station is completely isolated and a bulb can be changed in about twenty minutes.

Track feeders are provided with automatic re-closing circuit breakers on the positive side, and contactors on the negative. The intervals at which the breaker re-closes is adjusted according to requirements, but a typical case is as follows : First time within ten seconds ; second time within ten seconds ; third time after one minute ; fourth time after two minutes, the various breakers being arranged so as not to re-close simultaneously after a shut down.

If a breaker has opened due to momentary overload, it is essential that it re-closes after a short interval, for the driver with the free

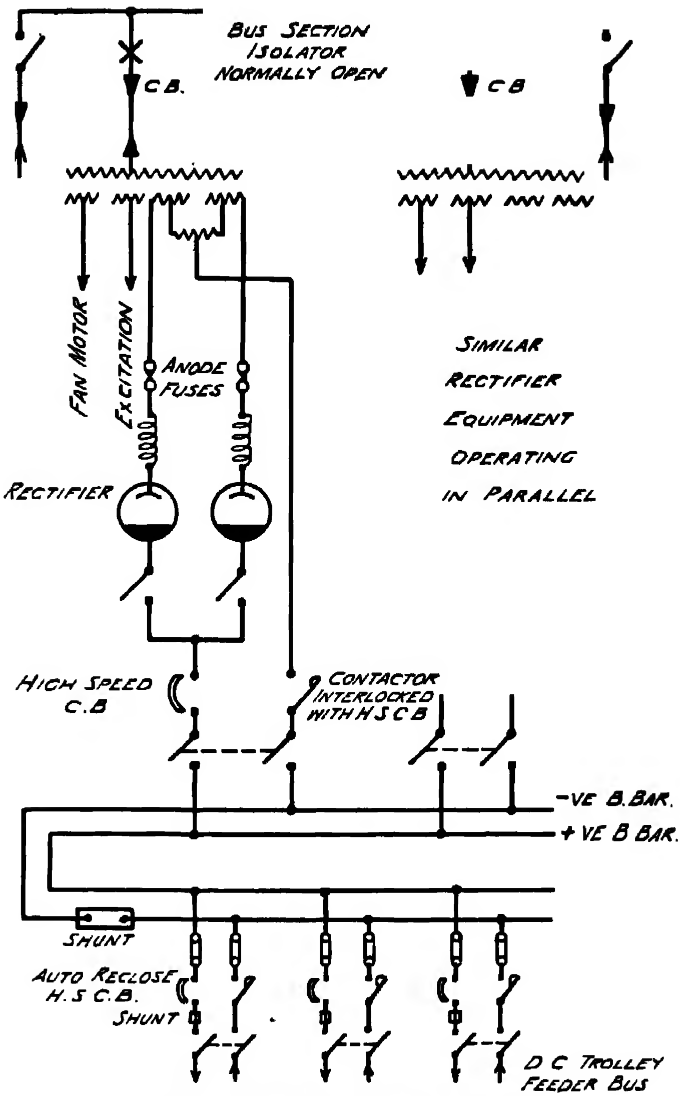


FIG. 205. Rectifier sub-station for trolley-buses.

momentum of a trolley bus does not realise (unless luminous indication is provided) that current is off, and if the breaker is re-closed too late

the slowing motors, without any resistances in circuit, will be subject to full voltage. Two quick re-closes will usually clear any overloading conditions, and the one or two minute intervals give time to clear short circuits caused by de-wirement. To cater for bigger mishaps, two push-buttons may be installed at each feeder pillar. The " open " button when depressed can be held down by a catch ; the circuit breaker in the sub-station is thus opened and cannot be re-closed. In this way, the traffic or electrical staff can ensure that in the event of

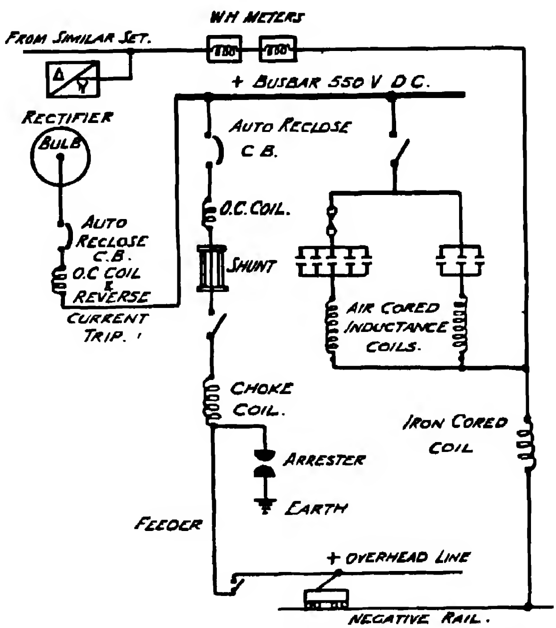


FIG. 206. Glass-bulb rectifier equipment for traction service.

trouble on the overhead lines the track remains " dead ". The circuit breaker is re-set by releasing the catch and depressing the " close " button. If a breaker has to be locked out, there is no need to go to the sub-station to re-set it ; depressing the " close " button at the feeder pillar brings the re-close cycle into action again. On some systems motor convertors and rotary convertors run in parallel with distant rectifier sub-stations but not on the same busbars in any one sub-station. Figs. 206–208 show typical systems. Insulated return

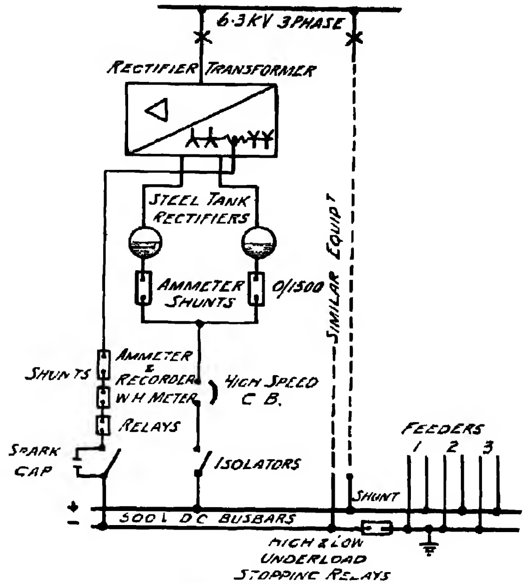


Fig. 207. Main rectifier connections.

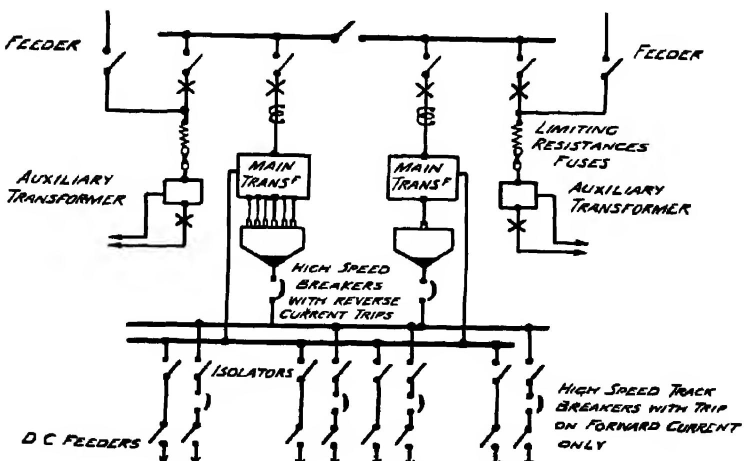


Fig. 208. Typical diagram of traction system rectifiers.

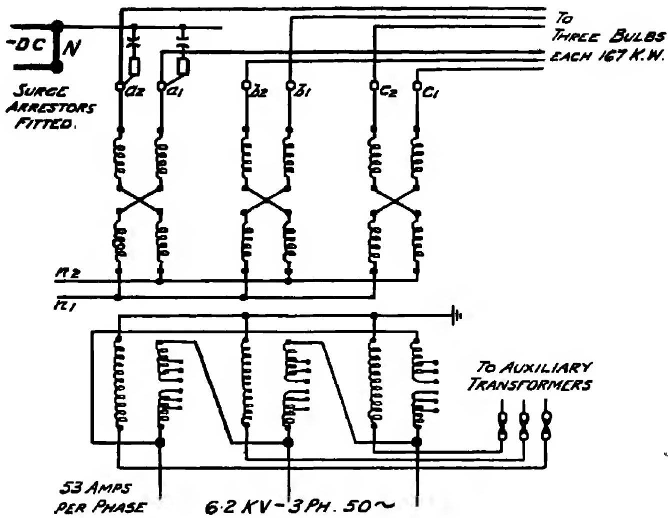


FIG. 209. Main transformer.

trolley-bus systems require a circuit breaker in the negative pole. Figs. 209–213 show typical rectifier connections. Table 19 giving operational data for certain rectifier sub-stations will serve as a guide when considering such plants.

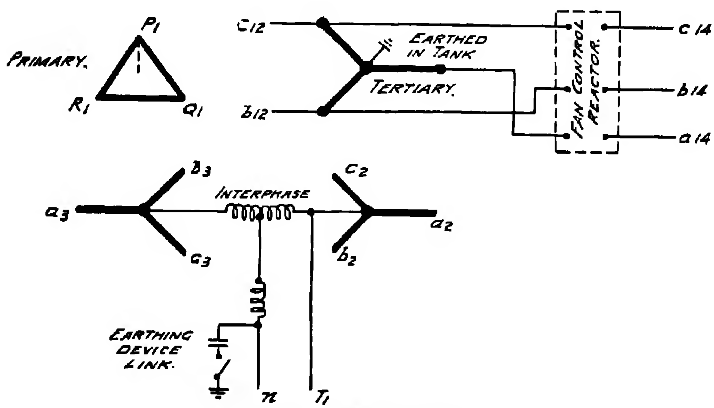


FIG. 210. Vector diagram.

TABLE 19. *Rectifier Sub-stations—Annual Operational Data*

(Trolley-bus Supplies)

Sub-station	Plant Installed kW.	Total Running Time H—M	kW Hours		Efficiency %	Station Load Factor	Maximum Demand kW (D C)	Remarks
			A C. Input	D C Output				
1	2–230	6,477–0	363,870	295,310	81·2	24·1	140	Glass-bulb
2	2–350	5,842–15	638,750	539,130	84 4	30·8	200	Glass-bulb
3	2–350	17,520–0	919,640	827,360	90·0	26·2	360	Glass-bulb
4	2–450	54,12–0	1,256,360	1,133,400	90·2	24 9	520	Steel-tank Pumpless

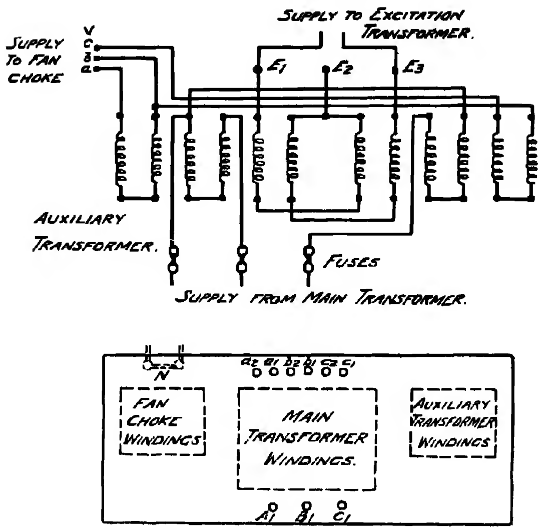


FIG. 211. Auxiliary supply transformer.

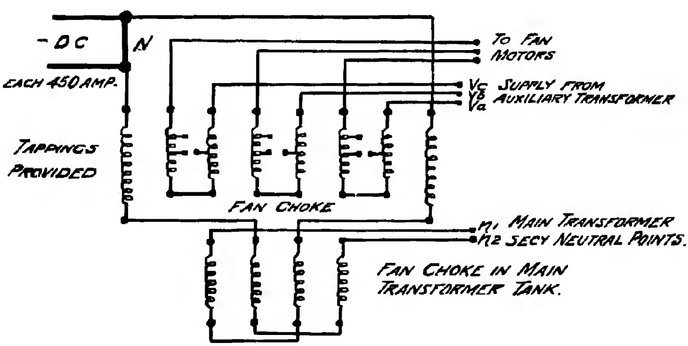


FIG. 212. Fan choke circuits.

Regenerative Braking. Troubles have been experienced with trolley-buses fitted with regenerative braking causing rotary convertors to trip out due to reverse current. Tests indicated that reverse current up to 350 amps. could occur and that a reverse current exceeding 100 amps. might be sustained for two seconds. On isolated sections

supplied from rectifiers it was observed that voltages approaching 810 volts were possible which affected certain voltage relays.

Excessive voltage rise due to regeneration may be prevented by including a loading resistance. An Ignitron loading equipment may also be used, for which it is claimed that excessive voltage rises are limited and that no sudden load is thrown on the traction motors. The main loading resistance used with this equipment has a short time rating of 200–300 amps. One device or over-voltage suppressor comprises a three-arm rectifier glass-bulb with grid bias on the arms and the usual excitation anodes. The main arms are biased to have voltages of 580, 610, and 640 volts above the cathode so that with a 580 V supply the first arm will have a 30 V bias, the second arm a 60 V and the third arm a 90 V bias. When over-voltage occurs exceeding 580 V No. 1 arm passes the current which closes a contactor, putting a resistance across the busbars, and when the voltage falls below 580 V the grid bias at once stops the current through the rectifier. There is a delay feature on the contactor holding in a resistance until the power reverses due to the supply being taken from the sub-station when a contactor opens. Should the voltage exceed 610 V the second arm comes into action as well as the first arm, and when the voltage reaches 640 V the third arm is in operation, all in parallel. The action of the bulb is very quick, being the order of 1/1,000 part of a second. This can be further reduced if desired. The constant loss is of the order of 200 watts. This device also has an arrangement for limiting the voltage rise which takes place when no load is on the rectifier. This is obtained by means of a small resistance switched across the line. The equipment is accommodated in a small cubicle with the relay on a panel at the back.

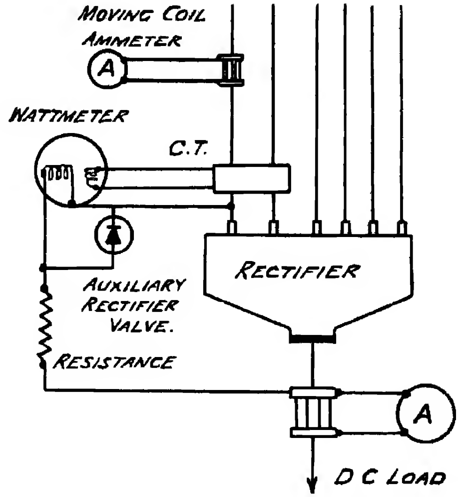


FIG. 213. Test connections for arc loss.

To overcome the possibility of isolating sections of the overhead trolley system the Hastings coupler can be used, and series dynamic control can be included in the motor circuits.

D.C. Three-Wire Supplies. Figs. 214 and 215 show main connections for affording such supplies.

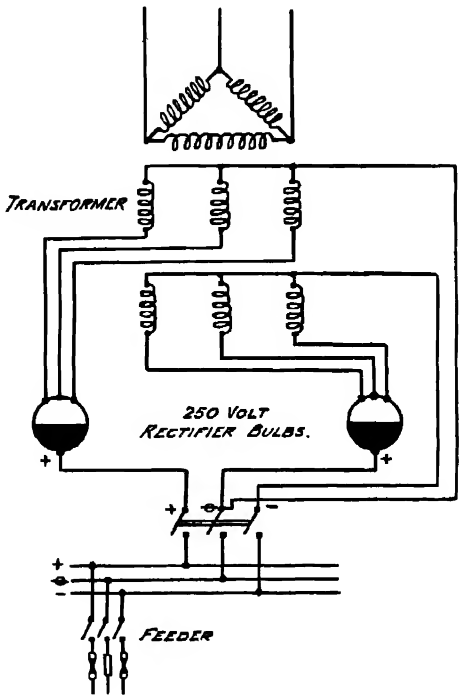


FIG. 214. Three-wire D.C. system.

A rectifier bulb was installed on the negative side of a system at a sub-station. Flickering voltage in the district supplied by the rectifier resulted only on the negative side. It was found that on little or no load the anode and consequently the terminal voltage of the rectifier varied. Excitation volts depend on excitation current and the excitation choke air gap was increased by approximately $\frac{1}{4}$ inch, thereby increasing the excitation current. This overcame the undesirable voltage variations.

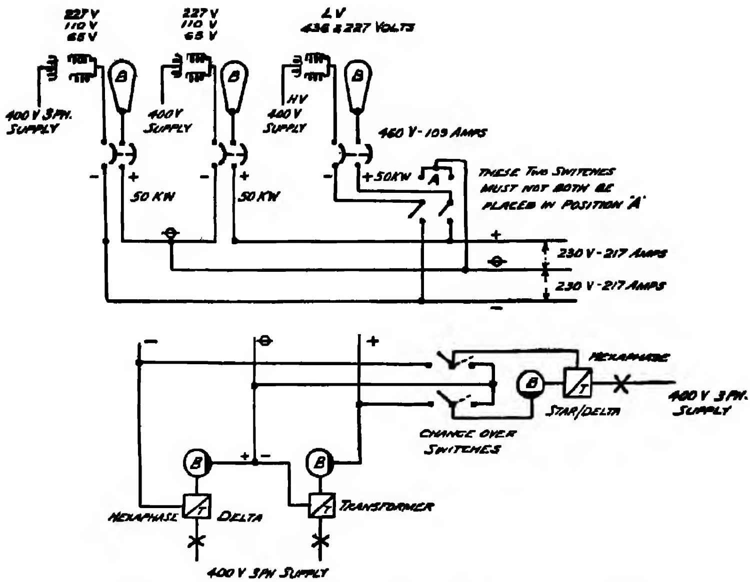


FIG. 215. D.C. three-wire system using glass-bulb rectifiers.

Traction Supplies[4] The D.C. voltages generally used are 600, 1,500 and in some cases 3,000. It is over this range of voltage that the mercury-arc rectifier operates most satisfactorily with high overall efficiency. An additional advantage is the fact that the operation is electronic so that it can respond to changes of load without any inertia effect, and there is no equivalent of the snatch which a large rotating machine suffers when a sudden overload is applied. For traction conversion plant it is usual to call for heavy overload characteristics in order to deal with the high short-time loads produced by accelerating trains. In this the mercury-arc rectifier might be considered at a disadvantage because it has an inherently short time-constant compared with transformers and rotating machinery. This difficulty is easily overcome by providing suitable rectifier capacity in relation to the transformer capacity installed. The essential advantages of rectifiers for traction supplies are :

(1) The fact that the rectifier can be left unattended for long periods.

(2) Their ability to meet overloads without any difficulty or mechanical stress when correctly designed.

(3) Their low losses on light load so that they can be left switched on indefinitely without serious loss of power.

In the supply of traction networks a relatively large number of small sub-stations can be erected at intervals throughout the system so that the majority of the transmission takes place at high voltage A.C. Whilst this is desirable for trains and trams it has been almost essential in the case of trolley-buses where the line drop in the two trolley wires is relatively high.

ROTARY CONVERTORS

The rotary convertor has been superseded by the rectifier for sub-station work. The field of application is now restricted to the operation of low voltage electrolytic plants, since for low voltages the rotary convertor is still superior to the rectifier from the efficiency viewpoint. Whereas in a motor generator the electrical energy is converted into mechanical energy and back again into electrical energy, in a rotary convertor the conversion of A.C. into D.C. and *vice-versa* is an electrical process. The single winding of the armature carries the difference of the A.C. supply and the generated D.C., and this difference reaches a minimum when the machine is carrying only useful or wattful A.C. For $\cos \phi =$ unity, the current heating loss of the three-phase convertor amounts to 56 per cent. of the loss in a corresponding D.C. generator, while for a six-phase convertor the heating loss is only 27 per cent. of the corresponding D.C. machine. This favourable characteristic accounts for its very high efficiency. Any change in the excitation of a rotary convertor does not affect the D.C. voltage, but it alters the power factor and the armature current. The brushes on the commutator are positioned so as to obtain the maximum voltage available in the armature. The various ratios (assuming 100 volts and 100 amps. at D.C. end) obtaining for different numbers of phases are approximately as given in Table 20.

TABLE 20. *Voltage and Current Ratios*

Number of phases	1	2	3	6	12
Volts across slip-rings	70·7	70·7	61·2	35·4	18·3
Current per ring at 1 p.f.	141·4	70·7	94·3	47·2	23·6

If the A.C. volts are maintained constant, the D.C. volts gradually fall as the load is increased, and the ratio of transformation does not remain constant for all loads. The relation between the number of poles, frequency and speed is the same as in the case of a synchronous motor, and those given in Table 21 are typical of convertors at varying outputs :

TABLE 21. *Frequency and Number of Poles*

Output . . kW	250	500	1,000	1,500	3,000
Number of Poles . Frequency 25 cycles .	4	6	6	8	12
Number of poles . Frequency 50 cycles.	4	6	8	12	16

In view of their improved performance, six-phase convertors are employed for sub-station service, and the connections used are one of the following :

(1) Double mesh ; in which the transformer secondary voltage = $0\cdot612\ E_{DC}$ and the transformer ratio = $1\cdot63 . \frac{\text{A.C. volts}}{\text{D.C. volts}}$,

$$i.e., \frac{\text{A.C. volts}}{\text{D.C. volts}} \Big/ 0\cdot612.$$

(2) Double star ; in which the transformer secondary voltage = $\frac{0\cdot612}{\sqrt{3}} . E_{DC} = 0\cdot354\ E_{DC}$, and if the primaries are in mesh, the transformer ratio = $2\cdot83 . \frac{\text{A.C. volts}}{\text{D.C. volts}}$

$$i.e., \frac{\text{A.C. volts}}{\text{D.C. volts}} \Big/ 0\cdot354.$$

(3) Diametral ; in which the transformer secondary voltage is doubled, thus halving the transformer ratio which = $1\cdot41 . \frac{\text{A.C. volts}}{\text{D.C. volts}}$

Rotary convertors are used in connection with three-wire D.C. systems of supply, Fig. 216, without a separate balancer set, providing

the neutral point of the transformer secondary is brought out. Convertors may be started up by means of :

(1) Auxiliary motor mounted on same shaft.
(2) From the D.C. side.
(3) From the A.C. side.

A rotary convertor can be used for converting D.C. to A.C., when it is said to be inverted, its speed depending on its field strength if

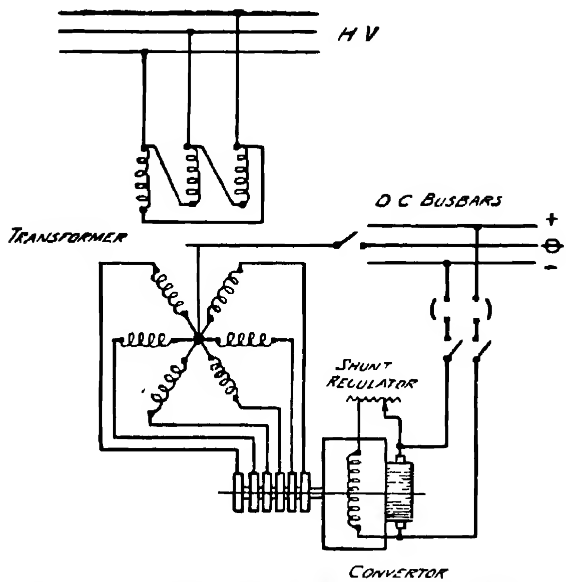


FIG. 216. Connections for three-wire rotary convertor.

running alone. When running alone, a weakened field results in a rise in speed, and should the load be inductive the lagging current may cause the speed to rise to a dangerous value. A direct-coupled exciter overcomes this trouble, for any increase in speed brings about an increase in exciter voltage with consequent strengthening of the convertor field. Convertors have their own transformers, as this prevents the setting up of cross currents between machines required to operate in parallel. The power factor of a rotary convertor depends upon its excitation—similar to a synchronous motor—and is operated at or near unity power factor. On full load, armature heating is affected by increasing the power factor to a leading value, and in a six-

phase machine the heating is increased by some 80 per cent. if the power factor is changed from unity to 0·9 leading. Some methods of obtaining voltage control on the D.C. side are :

(1) Reactance regulation—in which a special reactance coil is inserted in each phase between the transformer secondary and slip-rings, or, alternatively, the extra reactance may be provided by the transformer. This method is suitable for voltage variations up to 12 per cent.

(2) Booster regulation—in which additional voltage required at the slip-rings is given by a direct-coupled booster. The booster receives its excitation from the D.C. end of the machine, its field coils being connected in series with the load, similar to the compounding coils. The power factor is independent of the load, so that unity or leading power factors can be obtained as desired. It is suitable for voltage variations up to 25 per cent.

(2) Booster regulation—in which additional voltage required at the slip-rings is given by a direct-coupled booster. The booster receives its excitation from the D.C. end of the machine, its field coils being connected in series with the load, similar to the compounding coils. The power factor is independent of the load, so that unity or leading power factors can be obtained as desired. It is suitable for voltage variations up to 25 per cent.

(3) Induction regulator control—in which the voltage generated in the regulator rotor depends on the position of the movable rotor. To prevent any alteration in the power factor, a variation in the boost voltage necessitates an adjustment in the excitation.

Automatic sets are popular for sub-station service and Fig. 217 (p. 278), shows a typical line diagram of connections.

Danielson Convertor. Another convertor is the Danielson type, although it is now rarely employed. A 500 kW set consists of an ordinary shunt-wound A.C./D.C. convertor with the addition of series field winding for inverted operation. At the commutator end of the driving shaft a Danielson convertor is fitted, a feature of which is that the pole pieces are without field coils. Its slip-rings receive A.C. (90 A at 12·5 V) through a series transformer energised from the main 6·6 kV transformer while its D.C. output of 60 A at 17 V excites the additional series field windings of the main rotary convertor when operating as an invertor. A booster with the rotor windings inserted between the main slip-rings and the armature is included. The field pole yoke of the booster is so designed that it can be rotated to retard or advance

the positions of the poles in relation to the machine field coils, thus permitting zero to $\pm$ 13 volts regulation, the booster rating being 40 kVA. The normal A.C./D.C. operation the secondary output windings of the series output transformer are short circuited and a resistance is inserted in the D.C. output from the exciter. For inverting D.C./A.C. the machine is run up to speed from the D.C. end through a tapped resistance and the speed adjusted by the main shunt field rheostat. After synchronising the high A.C. output voltage is controlled by shunt regulator in the booster field circuit.

MOTOR CONVERTORS

The motor convertor, Figs. 218 and 219, is essentially an induction motor with a wound rotor and a D.C. generator coupled together mechanically, and having an electrical connection. The stator of the motor is wound for the same number of phases as the supply, but the rotor usually has a twelve-phase winding. When starting, only three or six phases are used, these being connected to the slip-rings and the rotor starting resistance. A short-circuiting device is fitted for common connection of the twelve phases when normal running speed is attained. A synchronising voltmeter is connected across two of the slip-rings, and when the pointer is almost steady the starter and rings are shorted. In the case of a three-wire D.C. machine a change-over switch is provided. Motor convertors can be run inverted and can also be used for power-factor improvement. When used for the latter purpose, the convertor is started and synchronised from the A.C. side, whilst the D.C. side is over-excited and left disconnected from the busbars. When the number of poles of the two portions differ, the speed is inversely proportional to the sum of the number of poles of the motor and the generator. The stator winding is wound so as to run directly off the supply voltage. Assuming that the set is running at half the synchronous speed of the first machine and that each machine is wound for two poles. With a supply frequency of 50 c/s. the speed of the rotating field set up in the first machine is 3,000 r.p.m., and consequently the rotor winding is being cut by the rotating field at a speed of 1,500 r.p.m. The 25-cycle e.m.f.s. induced in the rotor winding are applied to the tappings of the armature, and therefore give rise to a magnetic field rotating backwards at 1,500 r.p.m. relatively to the armature and stationary relatively to the poles, if the tappings of the armature in the correct sequence. In other words, the second machine—regarded as a rotary convertor—is running at syn-

chronism, and a constant voltage is therefore obtainable from its commutator. The first machine is also acting partly as an induction motor driving the second machine as a D.C. generator. Taking the general case of the first and second machines wound for P_M and P_G pairs of poles respectively, we have—speed of rotating field in first machine $= \frac{60f}{P_M}$. If N be the synchronous speed of the set in r.p.m., frequency of e.m.f. induced in the rotor of the first machine $= \left(\frac{60f}{P_M} - N\right)\frac{P_M}{60} = f - \frac{N \cdot P_M}{60}$. Since this frequency is applied to the armature of the second machine, speed of rotating field of second machine relatively to its armature $= \left(f - \frac{N \cdot P_M}{60}\right)\frac{60}{P_G}$. But this field is stationary relatively to the poles,

$$\left(f - \frac{N \cdot P_M}{60}\right)\frac{60}{P_G} = N$$

$$\therefore N = \frac{60f}{P_M + P_G}.$$

The slip frequency $f_S = f - \frac{N \cdot P_G}{60}$

The frequency of the currents in the generator

$$= f \cdot \frac{P_G}{P_M + P_G}$$

and is always considerably lower than that of the supply, which ensures an improved machine performance. Motor convertors are not so liable to reversal of polarity as rotary convertors.

Power-factor correction is obtained by over-exciting the second machine, thereby causing the latter to take a leading current in the same way as any over-excited rotary convertor. Owing to the second machine acting partly as a D.C. generator, a variation of its exciting current is accompanied by a variation of its terminal voltage. This effect is accentuated owing to the reactance of the first machine altering the voltage supplied to the tappings of the D.C. armature just as in the choke-coil regulation of rotaries.

The motor convertor is started up like an ordinary slip-ring induction motor, the starting switch being open and the armature serving as the star-connection of the rotor winding. As the set approaches its

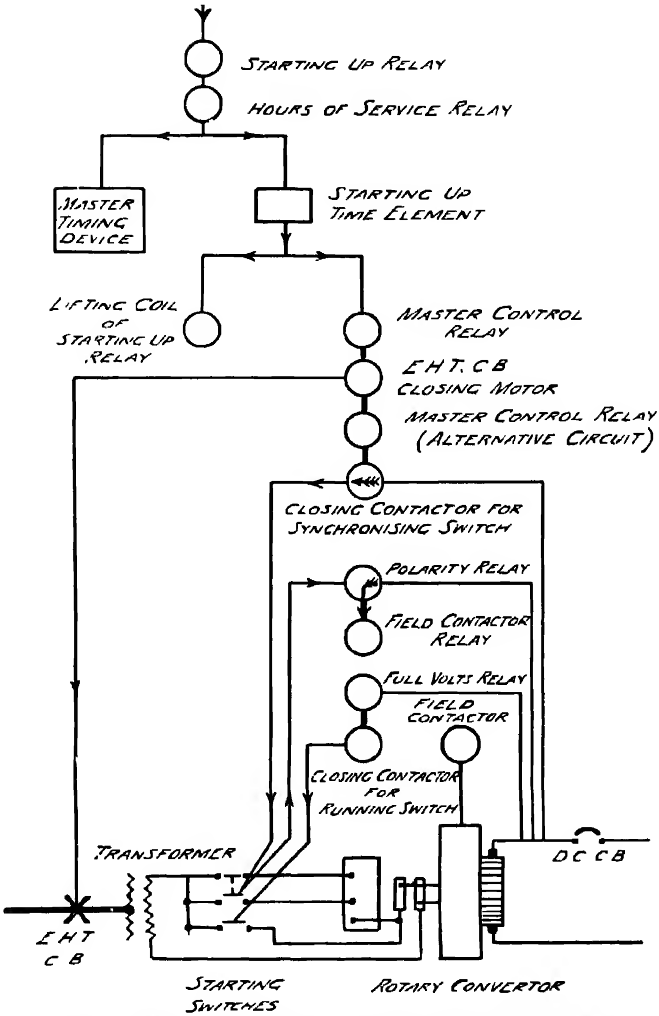


FIG. 217. Sequence of operation for automatic rotary convertor.

normal running speed, the second machine commences to excite and the voltmeter begins to oscillate, the frequency of these oscillations decreasing as the set gets nearer synchronism. A zero reading on

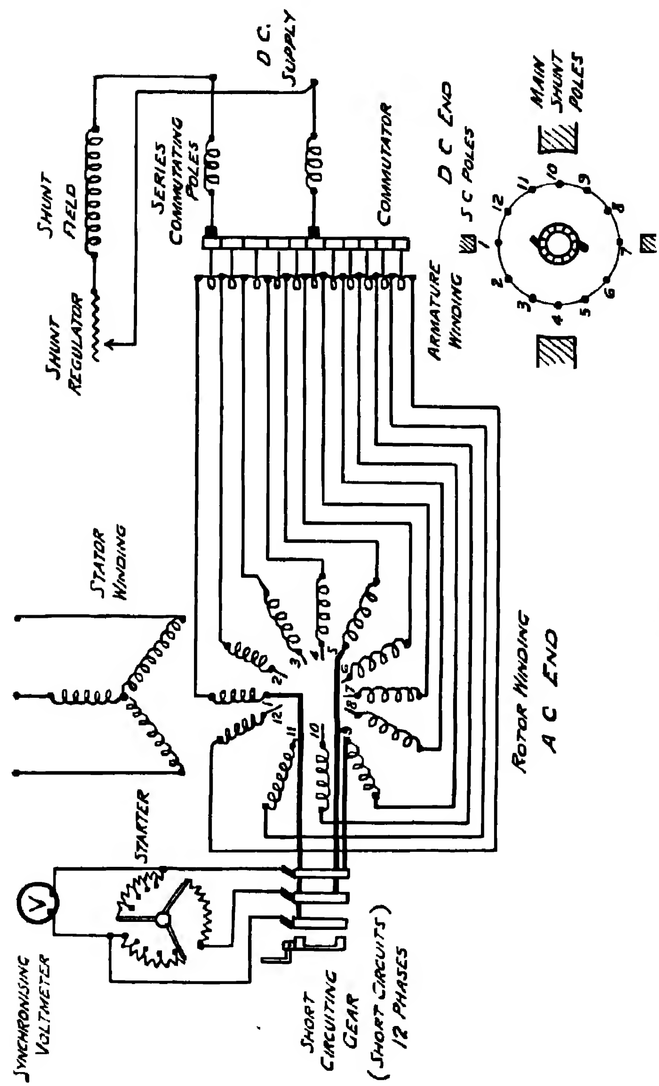


FIG. 218. Motor convertor connections.

the voltmeter means that the voltages induced in the corresponding phases of the rotor and armature windings are in exact opposition. The oscillations on the voltmeter are, therefore, made very slow by

varying either the starting resistance or the shunt regulating resistance and the starting switch can be closed when the voltmeter pointer is at zero, the set being then in synchronism.

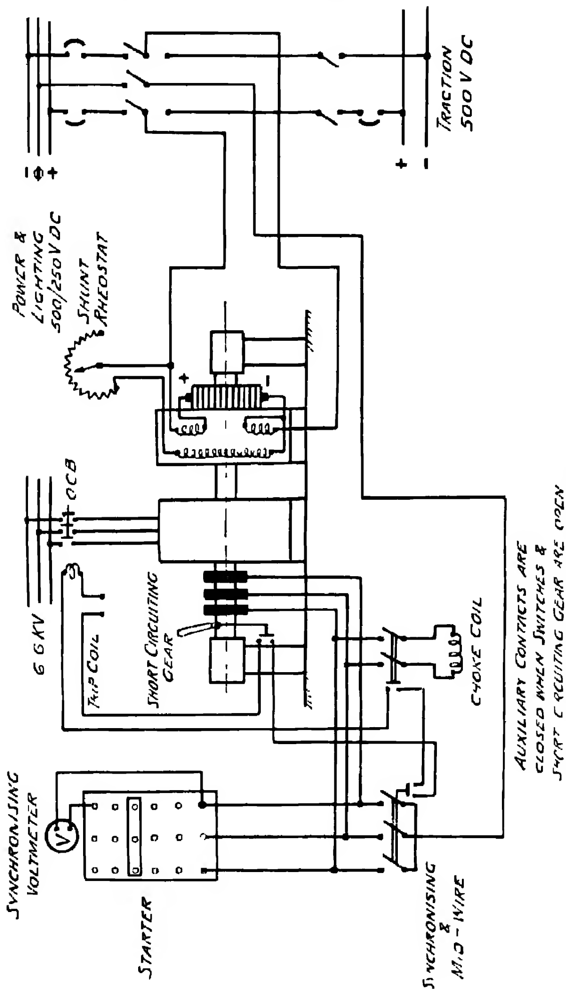


FIG. 219. Three-phase self-synchronising three-wire D.C. motor convertor (1,000 kW, 6·6/6·8 kV–750 R.P.M.).

FREQUENCY CHANGERS

These are used for linking together two electrical systems of different frequencies, either for normal interchange of power or, altern-

atively, to serve as a stand-by and to assist at peak periods. The frequency changers therefore have to be reversible in their functioning in so far as power transfer is concerned. The changer consists of two machines mechanically coupled and so designed that each machine is capable of running either as a motor or an alternator, in order that electrical energy may be transferred in either direction. Induction machines may be used, but it is more usual to have synchronous machines. As the machines are rigidly coupled, and also connected to electrical systems of different frequency, the synchronous speeds of the two machines must be equal. Such a condition limits the choice of speeds for which any particular set may be designed. When the conditions necessitate a low speed, the cost of a set for certain frequency changes may be rather high. If $f1$ and $p1$ and $f2$ and $p2$ are the frequency and number of poles of machines 1 and 2 respectively, and N the speed of the set in r.p.m., then $N = \frac{120 \cdot f1}{p1} = \frac{120 \cdot f2}{p2}$.

The maximum speeds possible for the more usual frequency changes are given in Table 22.

TABLE 22. *Maximum Speeds*

Frequencies $f1$—$f2$	Poles $p1$—$p2$	Speed N
25—40	10—16	300
25—50	2—4	1,500
25—60	10—24	300
40—50	8—10	600
40—60	4—6	1,200
50—60	10—12	600

Assuming one machine of a frequency changer to be connected to system S1, the other machine must be in synchronism with system S2 before it is connected, and this condition is attained by varying the speed of one or both systems, *i.e.*, frequency alteration. After the machine is connected, the power transfer may be similarly adjusted. The set adjusts itself to normal fluctuations and acts in the same way

as an interconnector. The excitation for each machine may be taken from a common exciter, or, alternatively, from unit exciters as shown in Fig. 220, which ensures greater stability under system disturbances.

A pony motor is used for running up large sets. The stator of one machine is mounted on a cradle which is fixed to the bedplate, the stator being free to rotate in the cradle and the movement is effected by worm gear with either manual or electric-motor drive. Rotation of one pole pitch on the higher frequency machine is generally sufficient. The stator of one machine being movable enables the loading of each set to be controlled, thus preventing overloading. When one set is running the two systems are in step and have a phase displacement equal to that of the set. Should one machine of a second set be run up and connected to its respective system, the other machine of this

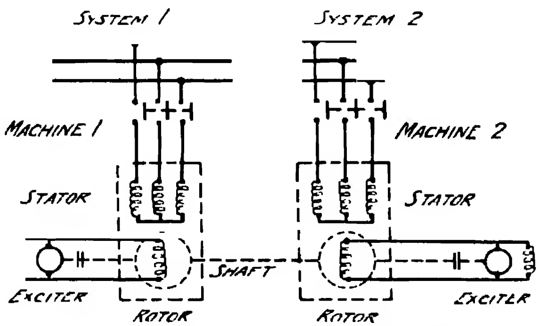


Fig. 220. Synchronous frequency changer.

set will be out of phase with its system by this angle. This is indicated by the synchroscope remaining steady but not in the 12 o'clock position for synchronism. Before connecting this machine to its system, the movable stator is rocked until the 'scope indicates correct synchronism, when the circuit breaker can be closed. The set is now coupled to both systems but carries no load, and the stator is adjusted until it takes up its share of the load.

When taking one of two sets running in parallel off load, all load should be transferred to the remaining set by rocking the stator forwards in the case of the alternator, or backwards for a motor, the circuit-breakers being opened when the set is floating between the two systems. When a single set couples two systems, any stator adjustment does not affect the load transfer, for each system automatically adjusts itself for such a change. The power transferred from system 1 to

system 2 depends entirely upon the adjustment of the turbines of one or both systems. The rotating stator is only used for synchronising and load sharing. A set may be started from either side and used as an emergency alternator in the event of failure of one of the systems. Frequency changers may be used for power factor improvement and this is effected by over-exciting both machines, causing the motor to take a leading current and the generatoı a lagging current. When separate exciters with automatic voltage regulators are provided for each set, power factor improvement is automatic, the set running near its full kVA capacity whether lightly or heavily loaded and independent of the direction of power transfer.

The rating of the machines and their exciters is dependent upon the desired range of power factor improvement. The synchronous

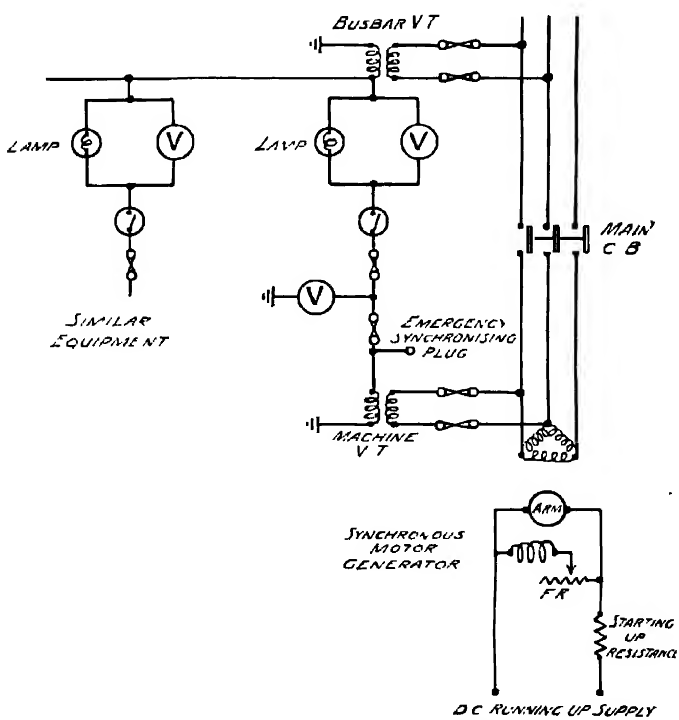


FIG. 221. Synchronising connections.

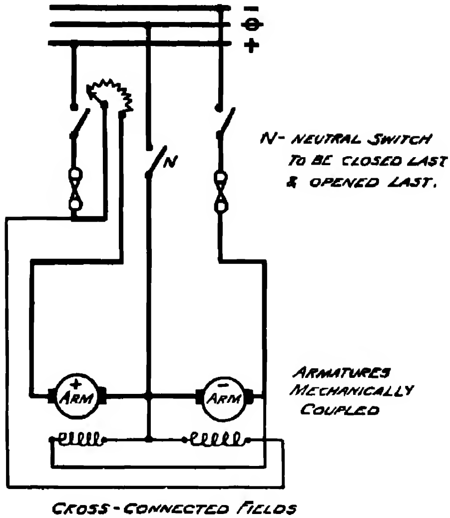


FIG. 222. Sub-station rotary balancer set.

frequency changer is suitable for interconnecting a small system with a large one, provided that the power to be transferred is not greater than, say, half the capacity of the smaller system. For systems with stable operating conditions, *i.e.*, small variations of load, frequency and voltage, and where power factor improvement is desired, then sub-station attendants are required. Other types of frequency changers are : a synchronous set with commutator cascade; a synchronous set with Kraemer cascade ; induction convertor with D.C. auxiliaries.

A 2,000 kVA, 11 kV set was supplying at 50 c.s. from the main station 25 c.s. system when the excitation of the 25 c.s. set suddenly increased to a maximum and immediate adjustment of the exciter field had no effect. As the effect of maximum excitation was to increase the stator current also to a maximum a second set was run up and paralleled and the defective set shut down. Investigation showed that a short circuit had developed in the cables from the shunt field to the rheostat.

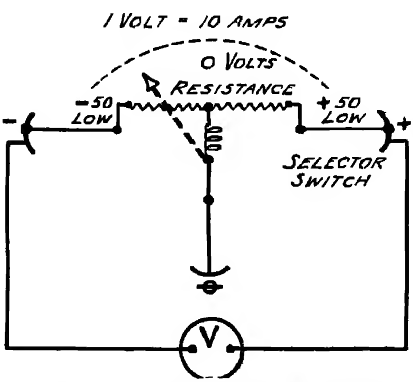


FIG. 223. D.C. 3-wire balance indicator.

Motor Generators and Balancers. Synchronous motor generators are sometimes used for sub-station service, and Fig. 221 gives a typical diagram of connections. Three fundamental requirements which must be satisfied—whether a turbo-alternator, a rotary convertor or a synchronous motor—is

connected to the busbars, are that the magnitude, frequency and phase of the voltage of the incoming machine shall be as nearly as possible equal to that of the busbars. The principal object of any synchronising equipment is to ensure that the supplies shall be paralleled only when these requirements are met. The main connections for a rotary balancer set are given in Fig. 222 and a three-wire balance indicator is shown in Fig. 223.

Bibliography

T. H. CARR. "The Choice of Converting Plant for Works' Services," *Mechanical World*, 21st September, 1945.

T. H. CARR. "Frequency Changers," *Power and Works Engineering*, Dec. 1951.

C. DANNATT. "The Metering of Mercury Arc Rectifier Supplies and Outputs," *Journal I.E.E.*, Vol. 81, 1937.

G. HAYNES. "Synchronous Frequency Changers," *Electrical Times*, 15th August, 1929.

E. P. HILL. "Rotary Convertors." (Chapman & Hall.)

F. J. LANE. "The Rotary Convertor Automatic Sub-station," *Journal I.E.E.*, Vol. 65, 1927.

E. A. LIVINGSTON. "Check Synchronising Equipment," *Journal I.E.E.*, Part 11, No. 54, December, 1949.

KURT LUBOWSKY. "Frequency Changers," *A.E.G. Progress*, April, 1926.

A. L. LUNN. "Equipment and Performance of Steel-Tank Rectifier Sub-Stations Operating on the Underground Railways of the London Passenger Transport Board," *Journal I.E.E.*, Vol. 78, 1936.

F. C. ORCHARD. "Mercury Arc Rectifier Practice." (Chapman & Hall.)

J. C. READ. "Rectifier Waveforms, *Electrical Times*, 24th April, 1947.

R. C. H. RICHARDSON. "The Commissioning of Electrical Plant." (Chapman & Hall.)

H. RISSIK. "Mercury Arc Current Convertors." (Pitman.)

J. W. RISSIK and H. RISSIK. "Heavy-Duty Rectifiers and their Applications to Traction Sub-stations," *Journal I.E.E.*, Vol. 69, 1931.

G. M. SLIGHT. "Carbon Brushes and their Application to Electrical Machines," *Mining, Electrical and Mechanical Engineer*, May, 1946.

A. STEVENS. "Mercury Arc Rectifiers," *Mining, Electrical and Mechanical Engineer*, May, 1949.

W. G. THOMPSON. "Recent Progress in Power Rectifiers and their Applications,' *Journal I.E.E.*, Vol. 83, 1938.

M. WALKER. "The Diagnosing of Troubles in Electrical Machines." (Longmans Green.)

R. WELLS. "Rectifiers in Parallel," *Electrical Times*, 15th May, 1947.

,, "Mercury Arc Rectifiers," *Electrical Review*, 8th August, 1947.

,, "Rectifiers for 3-Wire D.C. Systems," *Electrical Times*, 16th September, 1948.

,, "Arc Rectifier Theory," *Electrical Times*, 27th January, 1949.

CHAPTER VIII

ELECTRICAL PROTECTIVE EQUIPMENT

THE electrical protective equipment is so varied that it is only possible to deal with some of the principal systems and their associated apparatus. In general, the capital cost of a protective system only becomes of a comparatively high order when a pilot or special cable is required, otherwise its cost is small in comparison to the plant and equipment with which it is associated. The protective equipment may be grouped in accordance with the plant it protects, which, broadly, comprises the following : switchgear ; transformers and reactors ; rotary and motor convertors ; rectifiers ; motors ; and cables.

The primary function of any protective equipment is to isolate faulty plant with the minimum disturbance to the system. To minimise damage and disturbance due to a fault, the protective gear should operate rapidly and have comparatively low settings. Apart from being capable of operating rapidly, the protective gear must also be capable of remaining inoperative when the plant protected is healthy but carries maximum fault current which is flowing into faulty plant beyond it. This fault current is termed the " straight through current ". The stability ratio is the ratio of the maximum through faulty current at which the relay remains inoperative to the minimum fault setting (or sensitivity), or may be expressed as

$$= \frac{\text{Through fault current which causes false tripping.}}{\text{Internal fault current which causes correct tripping.}}$$

The sensitivity of a protective system may be defined as the minimum fault current to which the system is operative when a fault occurs within the protected zone. A protective system, the stability of which is independent of the other protective systems, or faults on other plant, and the operation of which extends only over the unit it protects, is said to provide " unit protection ". Examples of this are Merz-Price and Restricted Earth Leakage.

A protective system the stability of which is dependent upon the operation of protective systems of other plant, and the operation of

which extends over a range of protected or unprotected plant, is said to provide "back-up protection". Examples are Over-current protection, High Rupturing Capacity Fuses, and Unrestricted Earth Leakage protection.

Protective equipment should be capable of repeated operation under abnormal conditions, be reliable, easy to adjust, suitable for extension to existing systems, and reasonable in cost. Instability if the result of differences in the transformation characteristics of current transformers operating the protective equipment, which cause an out-of-balance current to flow in the relay circuit, results in false tripping. Transformers of liberal design improve the stability, as lower relay settings are possible without reducing the stability ratio.

Protective Gear Components. Some of the components associated with electrical protective equipment are : current and voltage transformers ; relays ; trip coils and time limit fuses ; pilot cables and operating circuits, which include the primary and secondary A.C. circuits and D.C. tripping circuits and their supplies.

Current Transformers. The bar primary current transformer is by virtue of its construction more able to withstand the conditions set up during system faults than the wound type. It is so constructed that electro-magnetic forces do not displace the windings, and is regarded as ideal from the standpoint of thermal and mechanical security under primary fault conditions. Certain difficulties arise in both the bar and the wound types in the lower ratios, *i.e.*, below 100 amps. primary current. The output of the bar type is limited and the short-circuit capacity of the wound type may be inadequate. One method of overcoming this is to use the bar type and limit the V.A. burden by providing separate transformers for instruments and relay operation. The bar-primary type provides a better flash-over value than the normal wound type and although inaccurate (not up to Class D accuracy) is quite suitable for protective gear purposes. The function of protective gear current transformers is to give maximum protection, both sensitivity and stability, and is not necessarily allied to any existing class of accuracy. The minimum ratio for a practical design of bar type transformer appears to be 30/1 amp., the output being very small, probably just sufficient to operate a sensitive over-current relay or a low V.A. ammeter. Consequently, with switchgear controlling low current circuits, it may only be possible to provide a relay setting to cover fault conditions approaching several times full load current.

The overcurrent factor of a current transformer is given by : $\frac{I_{RMS}}{I_{FL}}$, *e.g.*, with a fault current of 16,000 amps. R.M.S. and a 200/5 C.T., the O.C.F. $= \frac{16,000}{200} = 80.$

In many cases it is preferable to install two sets of current transformers—one for the operation of integrating meters, and the other for instruments and protective relays. Such an arrangement simplifies design, ensures satisfactory service for each duty, and may effect economy of core material. The magnetising ampere-turns necessary to excite the core of a current transformer are only a small proportion of the total primary ampere-turns, usually less than 1 per cent. The vector difference of the primary ampere-turns is balanced by the secondary ampere-turns, and if the secondary be open-circuited, the whole of the primary turns are available to magnetise the core. This may produce an abnormally high flux density, resulting in heating and a secondary voltage with a high peak value causing damage to the insulation and core. B.S.S. 81—1936 comments on this aspect, and states that the secondary circuit of a current transformer should be kept closed when current is flowing in the primary. Some engineers stipulate that the secondaries should be capable of withstanding open-circuit conditions with full primary current flowing. Such a test imposes additional considerations in the design of current transformers, the turn ratio being kept as small as possible, *e.g.*, where the primary current is 1,500 amps., it is so arranged that the protective system has 5 amp. secondaries, to keep the secondary voltage to a minimum. Substantial insulation between layers is provided, and the turns are arranged in relation to each other to avoid unnecessary high voltages between conductors. Where the maximum primary current does not exceed 1,200 amps., the secondaries may be short-circuited direct, but above this figure they should be shorted through a resistance.

If a current of 5 amps. is to flow through the secondary when the primary has its full rated current flowing, the ratio of the secondary to the primary is fixed, *e.g.*, if 1,000 amps. pass through one primary turn the secondary turns will be $\frac{1,000 \, . \, 1}{5} = 200$. Probably 198 turns would suffice, the difference being to compensate for primary magnetising ampere-turns, resistance and leakage effects. One ampere secondary current is used where distances between circuit breakers, trans-

formers and relay control panels are exceptionally long. To determine the correct connections for current transformers, reference should be made to the appropriate B.S.S. group and Fig. 224 shows method of checking polarity. Tests are facilitated by providing test windings on the current transformers, as it is unnecessary to isolate a feeder, or if a feeder is isolated, tests can still be carried out. Test windings avoid the disconnection of secondary connections, and the making of temporary ones to busbar spouts, etc.

When an earthing or neutral point is required, a current transformer is provided for protective or indication purposes. The practice is to connect this transformer on the earthing transformer side of the resistor, in which case it is subjected to a voltage of $E/\sqrt{3}$ on the

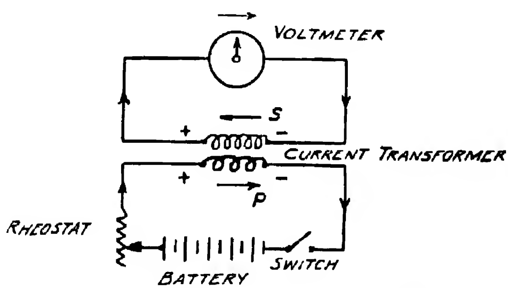


FIG. 224. " Kick " test polarity check.

occurrence of an earth fault.. Under such a condition, the earth side of the resistor would be insulated for a lower voltage. With a liquid resistor the tank is connected direct to earth, and should the earth plate develop a high resistance, the earth connections will be raised to a potential of line to earth voltage, *i.e.*, $E/\sqrt{3}$. The increasing popularity of high voltage air-blast circuit breakers, which have no bushings on which bushing type current transformers can be mounted, has resulted in an increased demand for separate self-contained high voltage current transformers.

Current transformers should have accurate ratio and phase angle ; be reliable ; and occupy a minimum of space. Current transformers for balanced protection, such as Merz-Price and Restricted Earth Leakage Systems, should have D.A.G.'s to avoid magnetic saturation of the cores under heavy fault conditions.

Voltage Transformers. Are used in connection with directional protective systems and instruments. They are similar to power

transformers, except that care is taken with the core construction, leakage reactance being eliminated as far as practicable, and low densities of flux and current used to ensure constancy of ratio. With a voltage supply for directional relays it is necessary to ensure operation with fault currents of low power factor, and the voltage is arranged to lag the current in the current coils of the directional overcurrent relays

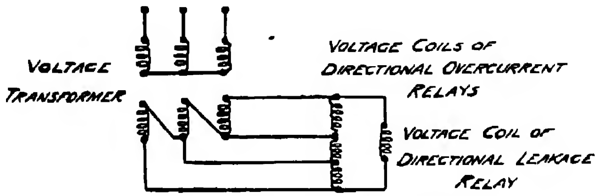


FIG. 225. Star-delta voltage transformer.

by 30°. Directional leakage relays require a voltage supply proportional to the residual voltage to earth, and this can be obtained from an open delta secondary winding, Fig. 225. The voltage coils of directional overcurrent relays can be energised from the same transformer. Fig. 226 shows an auxiliary voltage transformer with delta-connected

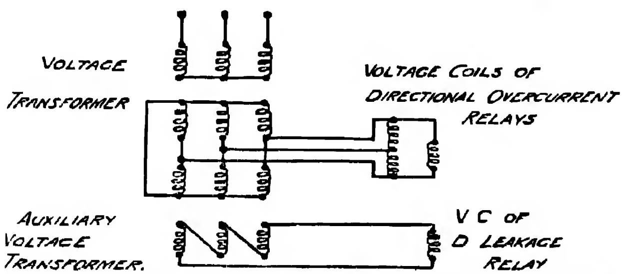


FIG. 226. Star-star voltage transformer with auxiliary transformer.

secondary for use with a star-star voltage transformer. For voltages of 66 kV and over, special forms of voltage transformer connections are in use, the compensated arrangement being typical. Voltage transformers are connected to the lines by way of fuses, but these are more in the nature of system protection than to afford protection to the transformers.

Relays. There are three general types, namely, Instantaneous ; Definite Time Limit ; and Inverse Time Limit, their application being according to the system of protection afforded. A relay should be of

sound and simple design and as robust as possible consistent with the sensitivity desired. Features requiring special attention in design are : bearings ; contacts ; movements ; and insulation. Point pivots, jewels, knife edges, and plain bearings are common, while contacts may be of platinum, tungsten, silver, etc. Electro-plated contacts are not satisfactory, for after a time the plating tends to crack and peel and an oxide film forms beneath it. A low voltage tripping circuit may become inoperative due to the high contact resistance offered by such a condition.

The movements are of the horseshoe, constant air-gap, solenoid and induction types, depending on the relay used. Moulded insulations are now quite common and have facilitated design and construction. Relays have a flag indicator fitted to each pole, the relay and indicator operating coils being connected to the negative pole of the tripping battery to minimise the effect of electrolysis. The Inverse Time Overcurrent Relay is popular for many electrical systems. The relay has two controls, a current plug setting (P*m*), and a time-setting multiplier (T*m*). The current plug settings range from 50 to 200 per cent. in steps of 25 per cent. for overcurrent relays, and 10 to 70 per cent. in steps of 10 per cent. for earth leakage relays. The time multiplier ranges from 0 to 1·0 in steps of 0·05. The current plug setting alters the number of turns on the relay coils, and, hence, alters the torque on the disc if the relay is not saturated. The current plug affects the time of operation as well as the pick-up current. The plug setting (P*m*) alters, in effect, the current transformer ratio. Thus a 400/5 transformer operating a relay with a plug setting (P*m*) of 50 per cent. is equivalent to a 200/5 transformer operating the same relay with a plug setting of 100 per cent. The pick-up current is that at which the relay starts to move. A 5-amp. relay set at 100 per cent. has a relay full-load current of 5 amps. and a pick-up current of about 1·3 times this, *i.e.*, 6·5 amps. Similarly, at 200 per cent., the full-load current is 10 amps., and pick-up current 13 amps.

The relay characteristic curve is given as a time/plug-setting multiplier curve where :

$$\text{Plug-setting Multiplier (P.S.M.)} = \frac{\text{Fault current in relay}}{\text{Relay full-load current}},$$

$$\frac{\text{Fault current in primary of C.T.}}{\text{C.T. full load} \times \text{plug setting per cent.}} \quad 100$$

A relay connected to a 400/5 transformer and set at 100 per cent.

would have a full-load primary current of 400 amps. ; if set at 150 per cent., full-load current would be 600 amps. With a primary fault

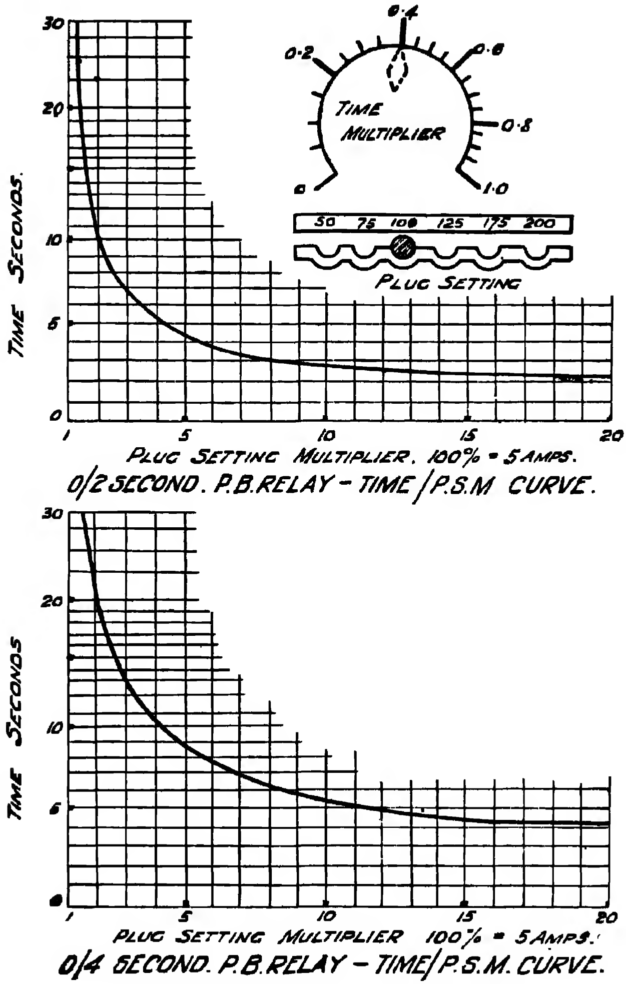


FIG. 227. Time-plug setting multiplier curves.

of 2,000 amps., the P.S.M.'s would be 2,000/400 and 2,000/600 respectively. If the fault current, plug setting and current transformer ratio are known, the P.S.M. can be determined, and a time

obtained from the Time/P.S.M. curve, Fig. 227. To calculate the time of operation of a relay, the following must be known : (1) Time/P.S.M. curve for relay ; (2) Current plug setting (P*m*) ; (3) Time setting (T*m*) ; (4) Fault current ; and (5) Current transformer ratio. An important feature is the plug-setting bridge, which allows the plug to be withdrawn and the relay automatically adopts the setting that it would have if the plug were inserted in the centre tap position. The setting may be changed on load without opening the current transformer secondary circuit and without a spare plug. Further, operation of the relay is assured even if the plug is inadvertently left out (100 per cent. setting). The percentage values marked on the current setting bridge refer to the current transformer rated current, and at these values the relays remain inoperative. With currents 30 per cent. in excess of the setting value for any setting (*i.e.*, 1·3S, where S is the setting), the relays operate in thirty seconds when the time multiplier is 1·0 (*i.e.*, the maximum), and in proportionately shorter times for other multipliers. For example, a current transformer of ratio 800/5 and set at 100 per cent. on the setting bridge would, as shown by standard curve, operate in thirty seconds with 1,040 amps. (*i.e.*, 1·3 × 800 amps.) when the time setting pointer is set at 1·0. Similarly, with 1,300 amps. (1·62 × 800 amps.) the relay operates in twenty-five seconds. It is necessary to ascertain the sustained fault current so that the plug setting is chosen to give the desired secondary current for relay operation.

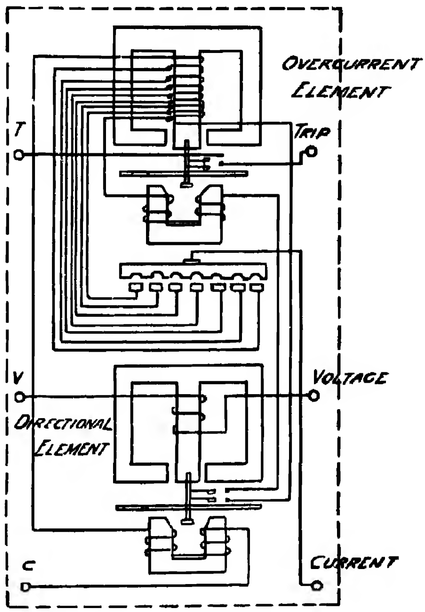


FIG. 228. Internal connections of directional relay.

Fig. 228 shows the internal connections of a directional relay.

Trip Coils and Fuses. Both A.C. and D.C. trip coils are used, the former (Fig. 229) being comparatively cheap, and do not require a battery. D.C. coils are used on all large sub-stations which necessitates

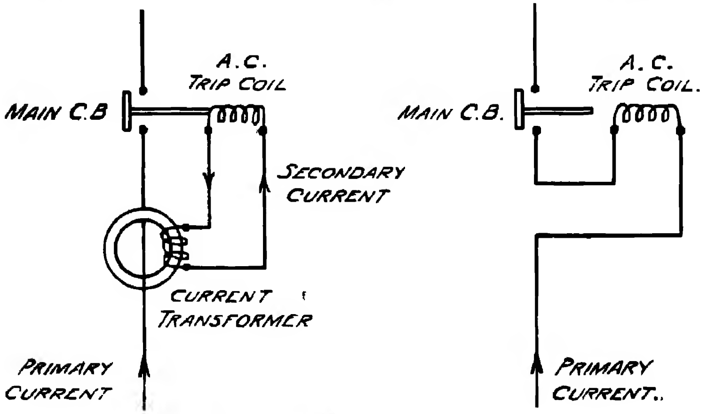


Fig. 229. Direct acting A.C. trips.

a battery. The simplest method of obtaining a delay action of over-current trip coils is to shunt the coils by time limit fuses, Fig. 230.

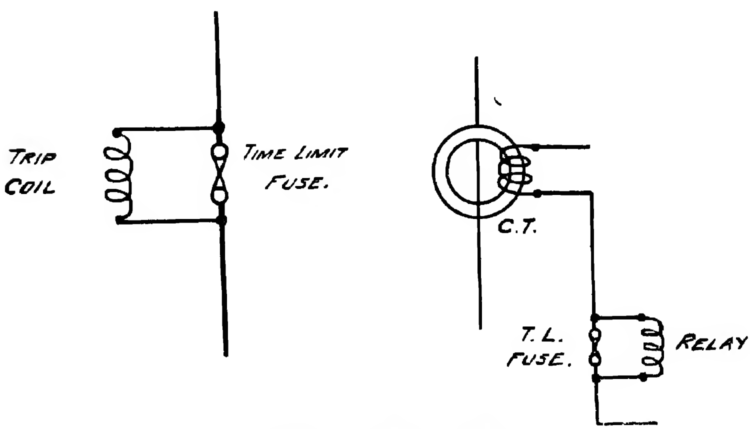


Fig. 230. Time limit fuses.

Care is required in design, manufacture and maintenance of these fuses if consistent performance is to be maintained. The fuse ends should be sweated and accuracy in dimensions and material of the fuse element

is necessary. Before putting fuses into service they should be subjected to about 60 per cent. of the minimum fusing current for half a minute to ensure that the wire has not been damaged by soldering. When a trip coil or relay is shunted by a fuse of low resistance, the majority of the current is diverted from the coil, which does not normally operate until after the fuse has blown. The sensitivity of the combination is thus determined by the fusing current and not by the setting of the trip coil or relay, which must be set to operate at a current value less than the fusing current of the wire. When connecting such apparatus it should be remembered that the relays are shunted across the fuses otherwise tripping of the relays will take place, without the fuses having blown. It is incorrect to shunt the fuses across the relays by comparatively long lengths of wire, for the reactance of these leads may, under fault conditions, be sufficient to divert most of the current through the relay coils, and so open the circuit breaker.

Some pole transformers are protected by cartridge-type fuses (11 kV, etc.) and other transformers up to and including 200 kVA units by liquid fuses. Above 200 kVA, circuit breakers with direct-acting A.C. trip coils are used to cover overcurrents and earth leakage. Where duplicate transformers are installed direct earth leakage protection is used to obtain discrimination. Some engineers do not favour the use of H.V. fuses on individual transformers as these frequently require replacement after a lightning storm when no apparent damage has been sustained by the transformer. A simple isolating switch on each transformer pole is often found quite suitable and then

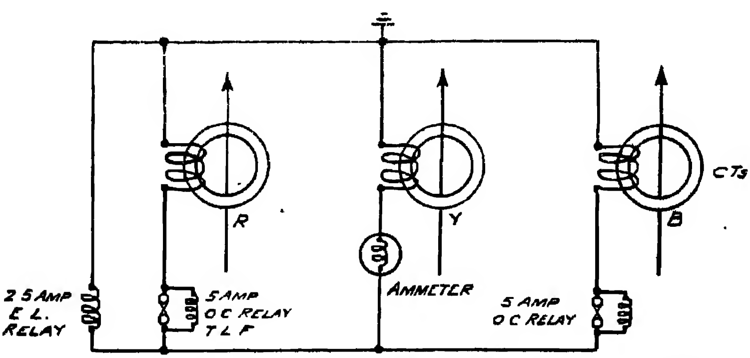


FIG. 231. Combined overcurrent and earth leakage protection. (Relays are essentially direct operating trip coils.)

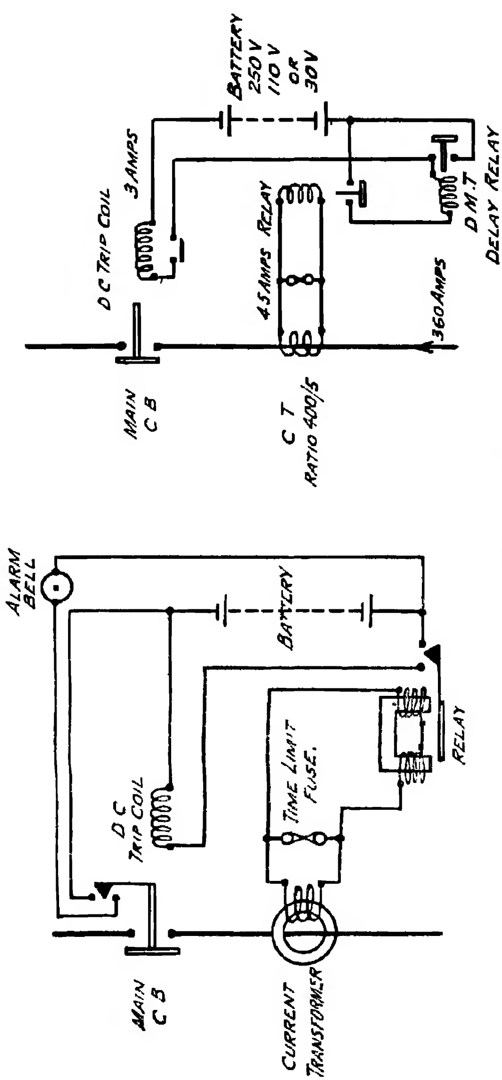


FIG. 232. Switchgear tripping circuits.

control the lines, suitably grouped, on automatic-reclosing switches. As a large number of faults are transient, the length of the interruptions will be kept to a minimum. If the secondary connections

of the current transformers are brought out to a terminal box they can be used with portable demand indicators to obtain loadings on the overhead lines.

Direct acting trip coils are connected in series with the circuit to be protected, and consist of an electro-magnet with a movable iron core, the pull exerted by the coil depending on the current flowing through it. Up to a predetermined current value, the pull is insufficient to lift the movable core, but above this value the core is lifted, causing a striking rod to trip the toggle of the circuit breaker. The current required for operation is varied by adjusting the height of the plunger within the coil. There are two extremes in setting—one with the overcurrent set high and a short time lag, and the other with the overcurrent set for normal current and a long time lag.

Time limit fuses are also used with relays and trip coils operated from current transformers. In the simplest form the trip coils and fuses are connected in parallel across the current transformers, one per phase. The fuses thus shunt the trip coils, and, when a fuse blows, the whole of the secondary current of the transformer passes through the trip coil. The circuit breaker, therefore, will not trip at any current less than full load of the current transformer. With combined overcurrent and earth leakage protection, the two overcurrent trip coils may be rated at 5 amps. and earth leakage trip coil at 2·5 amps. The tripping of the circuit breaker thus takes place with an earth fault equal to one half of the full load of the current transformer. In this case only two trip coils are shunted by fuses, Fig. 231, the

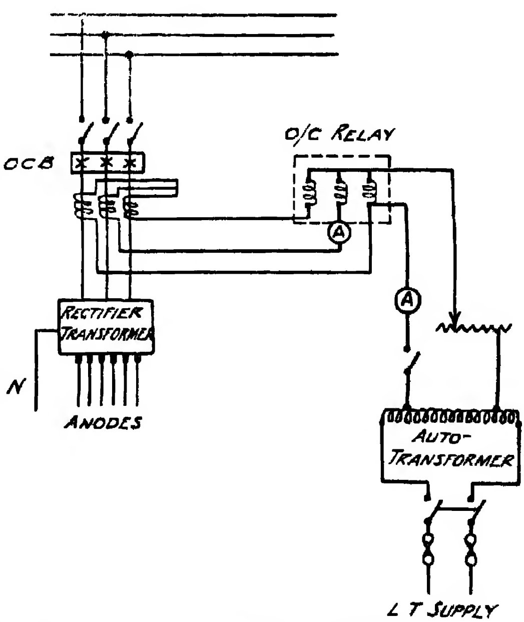


FIG. 233. Single-phase test on overcurrent relay.

earth leakage coil carrying the vector sum of the current transformer secondary currents, which is either zero or a very small value. The earth leakage trip coil is operated instantaneously, being independent of the blowing of a fuse. Typical tripping circuits are shown in Fig. 232.

Overcurrent Protection. A circuit may have its load balanced but at the same time be overloaded, and although balanced protection may be provided, it may still be desirable to have overcurrent protection to guard against excessive overloading of feeders and plant. The general application of overcurrent protection will be appreciated from accompanying diagrams. Fig. 233 shows test connections required.

Leakage Protection. This form of protection is generally applied with overcurrent systems, but can be adopted independently. It is used to obtain sensitive settings for faults to earth, which are by far the most frequent. The current fed into a circuit on one phase returns by way of one or both of the other phases, provided there is no leakage ; the secondary currents in the current transformers flowing similarly down one phase and back on one or both of the other phases, no current passing through the relay. On any phase failing to earth, the current in the secondary of the current transformer on that phase would return *via* the relay, as the impedance of the current transformers on the other phases is appreciable.

This system utilises three current transformers and three trip coils (alternative is relays). The two outer trip coils are connected direct to the positive terminals of two current transformers. The positive terminal of the third current transformer is connected to the star point of the trip coils (or relays) and the third trip coil is connected between this point and the star point of the current transformer secondaries. The two outer trip coils, which are shunted by time limit fuses, provide overcurrent protection. Under normal conditions the three-phase currents vectorially are equal to zero, there is no leakage or current through the leakage coil. When the phase currents do not fulfil this condition due either to a leakage or fault current in the main transformer (or equipment protected) or to the failure of a current transformer primary or secondary, current will flow in the leakage coil and trip the circuit breaker. This protection is not applicable where any part of the winding to be protected is earthed, such as on the star connected side of a transformer having the neutral point earthed. With 5-amp. current transformer secondaries and overcurrent relays,

and a 1-amp. earth leakage coil, the circuit breaker would trip instantaneously on an earth fault equal to 20 per cent. of the full load on the current transformers.

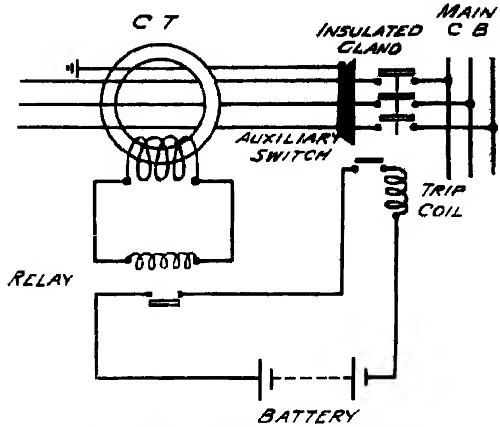


FIG. 234. Core balance protection.

The core-balance system, of which there are two main types, Figs. 234 and 235, depends on the resultant of the three primary currents being zero to remain inoperative. The sum of the return and outward currents being equal, there is no flux produced in the iron circuit of the transformer, and no current will flow through the relay. To ensure that the return earth fault current does not flow through the current transformer by way of the lead sheath of the cable and so neutralise the magnetic effect in the core, the sheath is earthed on the cable side of the transformer.

The core-balance system is a current-operated zero-sequence relay. This system may be used for the protection of lower voltage windings of a transformer. The three-phase leads and the neutral lead are taken through the core of a current transformer which carries a secondary winding, Fig. 236. Should any unbalance of the current in these four leads exist, it will cause the relay to operate. The neutral lead must only be earthed after it has passed through the core of the balance transformer. The leakage relay is usually arranged to trip both the H.V. and L.V. circuit breakers. This equipment can be designed to operate with a leakage current of some 7½ per cent. of the rated current.

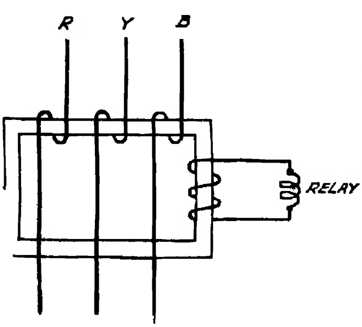


FIG. 235. Core balance protection.

Earth leakage protection may

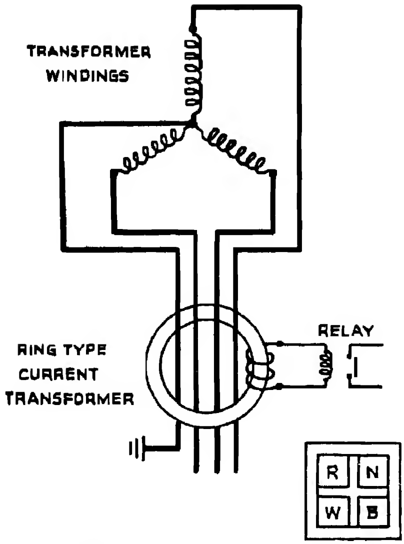


FIG. 236. Core balance protection.

operate without an earth fault being present on parallel circuits, *e.g.*, such a condition exists on closing a paralleling switch if all phases do not make contact simultaneously, for in this way current in one phase of one feeder may return partly on the other phases of the same feeder, and partly on the other feeder. A simple form of earth leakage protection is shown in Fig. 237 and is effective for internal faults in a transformer secondary winding, but it would also trip for any earth fault on the external secondary circuit. It is, therefore, not selective and would interrupt the whole supply from the transformer with an earth fault anywhere on the secondary system. Restricted earth leakage protection, Fig. 238, is only operative when earth faults occur within the protected zone. Busbar insulators have failed to earth and faults have persisted for a time sufficient to boil the earthing resistors dry. In addition to overcurrent protection, it is desirable to include unrestricted earth leakage protection, thereby safeguarding the system against earth faults of the type just mentioned. Another form of earth leakage protection is the direct system, which is still used on earthed neutral systems and in busbar zone protective schemes. The plant to be protected should be placed on reasonably dry material, *e.g.*, dry concrete, in such a way that the only metallic connection is made direct by the earth conductor, Fig. 239. An earth fault taking place inside or

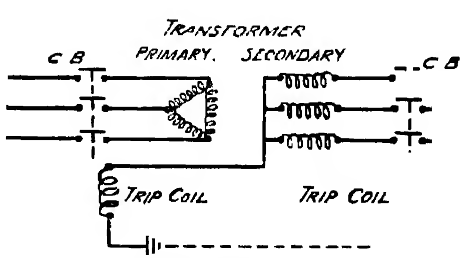


FIG. 237. Leakage protection to trip primary C.B. and/or primary and secondary C.B.'s.

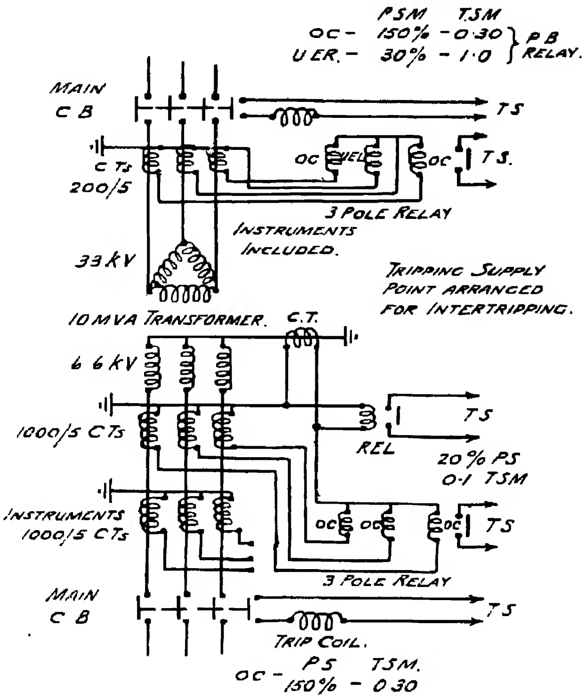


FIG. 238. Transformer protection (O.C.—U.E.L.—R.E.L.).

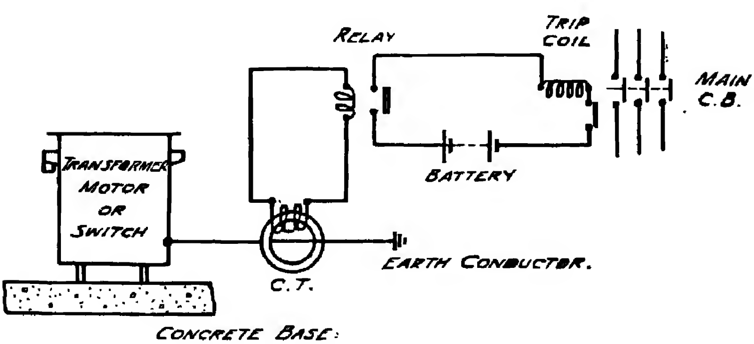


FIG. 239. Direct leakage protection.

between external terminals and the frame of the equipment will cause the relay to operate instantaneously and thus disconnect the faulty plant. The impedance of the current transformer is almost negligible, and the earth conductor can be made of adequate cross section so there is little risk of a dangerous voltage existing between the plant to be protected and earth. With a heavy momentary fault of, say, 1,500 amps., the primary voltage across the current transformer would not exceed 2·5 volts. Therefore, there is no danger of shock from the plant frame by the inclusion of the current transformer in the earthing conductor. A slip-over current transformer is used, but this does not necessitate a special earthing conductor. Good-contact making connections should be provided, and the relay should be calibrated with its current transformer, otherwise increased errors in the relay settings may be introduced.

The leakage currents vary over fairly wide limits, and the accompanying examples show applications in practice.

Case 1. A relay is required to operate with a leakage current of 120 amps., since it does not carry the current continuously a reasonably high current density is permissible, thus reducing the sectional area of the current transformer primary or earth conductor. A standard 200/5 current transformer is used with a relay of the overcurrent type. The relay coils—two in number—may be arranged to obtain any setting approaching 120 amps. leakage current. Four definite settings would suffice, and the settings obtained with a standard overcurrent relay of the horseshoe and armature type were as follows :

Primary current amps.		Secondary current amps.
80	—	0·95
100	—	1·05
120	—	1·15
140	—	1·25

Case 2. A relay is required to operate with a leakage current of 15 amps. in the primary of the current transformer. A standard 200/5 current transformer is used, but the overcurrent type of relay is not suitable for operation with such a small leakage current. It is, therefore, necessary to use a more sensitive type of relay. On carrying out tests with a sensitive relay of the Merz-Price type it is found that the lowest value of current to ensure satisfactory operation is 16 amps. This is probably due to saturation of the current transformer core.

The final settings marked on the relay dial are 15, 20 and 25 amps. and test figures are :

Primary current amps.		Secondary current amps.
16	—	0·10
22	—	0·16
25	—	0·18
27	—	0·20

It is necessary to know whether the tripping of a circuit breaker is due to earth leakage or overcurrent, and in mining work it is essential to record the former in the log book. The importance of A.C. earth-leakage protection is emphasised by the Mines Department, and is recommended as a means of protection covering not only the danger of electric shock, but reducing to a minimum the danger of electrical equipment, ignition of gases, and loss of output when a fault develops. The most common form of leakage protection employs a fixed design of current transformer, the sensitivity depending on adjustment of the relay for instantaneous or definite time-limit tripping. In another, the current transformer windings are varied so that the actual leakage current to earth can be determined, instead of stating a percentage of the full load current. In the Report of the Committee on the Amendment of the General Regulations governing the use of Electricity in Mines it is stated : " We recommend that it shall " (the measure of protection provided) " be such as to bring about automatic isolation of any circuit in which leakage to earth occurs exceeding 15 per cent. of the rated current for the circuit, or 5 amps., whichever is the greater."

The application of earth leakage protection requires care to avoid interruptions to large portions of a system. It would be unwise to install unrestricted earth leakage to a turbo-alternator or transformer (Fig. 240), except for stand-by service, in which case the time settings would be so graded as to be the last to trip.

The protection of rural overhead lines calls for some consideration, for it is possible to get fault conditions under which there is no over-current and but little earth leakage current, *e.g.*, a line breaking near an insulator may result in part of a conductor falling on to a fence, and the other end remaining clear on the pole. Negative phase sequence protection can be fitted, which operates with a given out-of-balance of the three-phase currents, *i.e.*, with single-phasing conditions. This scheme depends for its operation on the negative phase sequence com-

ponent of the line currents, which is obtained by means of a special connection of resistance and reactance in the current transformer circuit. The operating current is rectified before being applied to the relay which is essentially a moving coil milliammeter with two contacts. The making of the contacts closes the circuit of a definite time limit relay, which opens the circuit breaker. Overcurrent protection is provided by fuse shunted trip coils. During periods of very light load

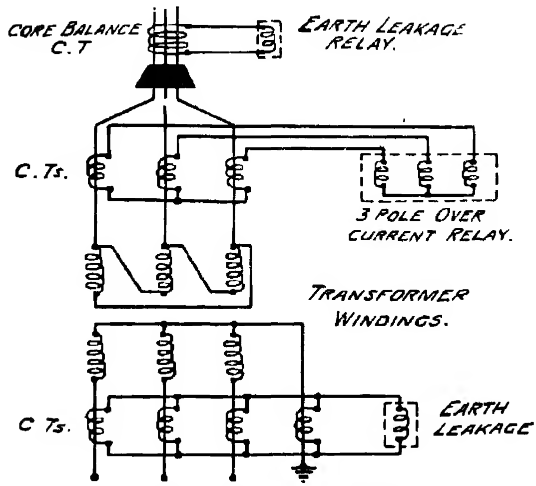


FIG. 240. Transformer protection.

the out-of-balance current caused by a conductor breaking may not be sufficient to operate the relay—a disadvantage of this form of protection. A reversed current transformer secondary will trip a feeder circuit breaker on earth leakage before the overcurrent setting value is reached, and a similar condition arises where a secondary lead is left disconnected.

Differential or Balance Protection. There are two fundamental systems of pilot wire balancing, namely, voltage or e.m.f. balance and current balance. Figs. 241 and 242 show them in simplified form. In the former, the secondaries of the current transformers at each end of the feeder are connected in series with the pilot wires and relays, so that under normal conditions their voltages are in opposition ; therefore no current flows through the relay coils. A fault fed in one direction allows one set of transformers to generate a higher secondary

voltage than its companion set, and the voltage difference causes a current to flow in the pilot wires and operate the relays. Should the fault be supplied from both ends the voltages become additive and increase the out-of-balance current operating the relays. The fundamental principle on which this system is based is that under normal

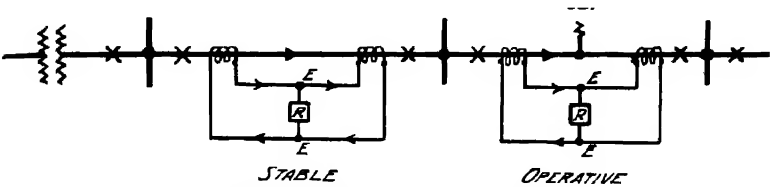


FIG. 241. Current balance protection.

conditions and neglecting losses, the current entering one end of a feeder is equal to that leaving at the other end ; as soon as a fault occurs, this condition no longer applies, and the difference between the incoming and outgoing currents is arranged to operate the relay and open the circuit breakers to isolate the feeder. Two similar current transformers of a suitable ratio are connected at either end of the feeder by means of pilot wires, so that when equal currents are flowing

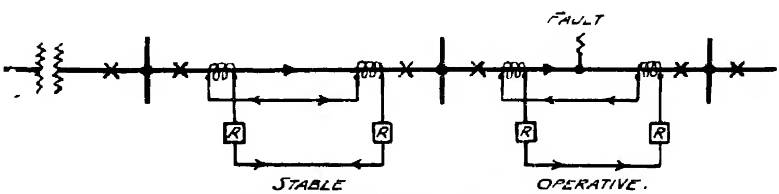


FIG. 242. Voltage balance protection.

in both primary windings the voltages of the two transformers are balanced against one another, with the result that no current will flow in the relays which are connected in series with the secondaries of the transformers. When a fault occurs the currents in the two primaries will differ from one another, in phase or magnitude, or both ; the secondary voltages of the two transformers will no longer be in balance, and as a result a current flows in the secondary circuit which operates the relays.

In the circulating current system, the transformer secondaries are connected so that current circulates when load or straight-through

currents flow. Each transformer produces an equal current, and the points of relay connection, E, being equipotential points, no current flows through the relay. On the occurrence of a cable fault, the transformers no longer produce equal currents, and depending upon whether the fault is fed from one or both ends, the difference, or sum, of the two currents flows through the protective relays. This system is based on the current balance principle, that so long as the transformer or other equipment is in good order the currents on the primary

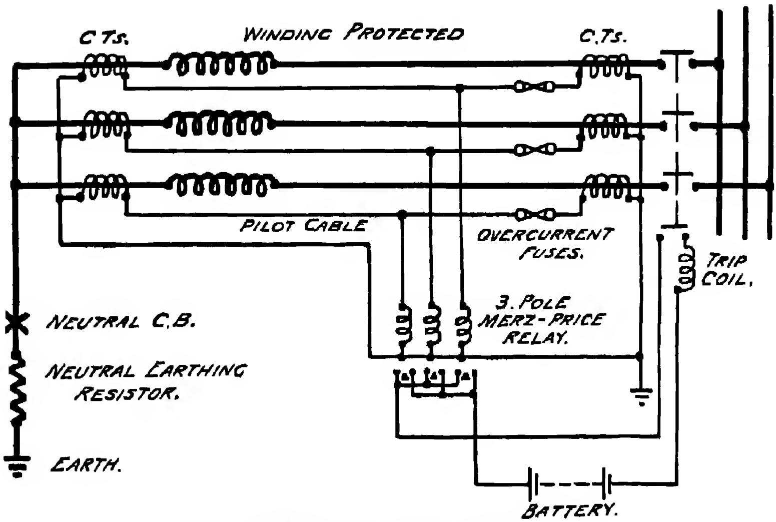


FIG. 243. Merz-Price circulating current protection.

and secondary sides are of the correct values, direction and phase relationship depending on the voltage ratio of the transformer, no current will pass through the relays. Current transformers of the correct ratios on the primary and secondary sides are so connected together, and to each other by means of short pilot cables, that the current flowing in the secondaries of the current transformers is equal, and normally there is no difference of potential between the middle points of the pilot wires connecting the secondaries. A sensitive type triple pole relay is connected between these pilot wires. The Merz-Price systems are based on these principles, and overcurrent protection may be provided by inserting fuses in the three pilot cables, as shown in Figs. 243 and 244. The fuses blow on the occurrence of a

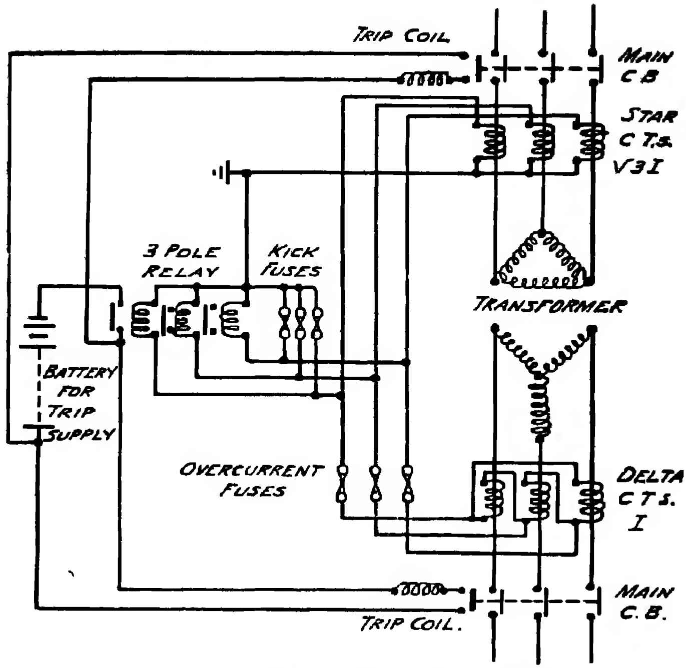


FIG. 244. Transformer protection (Merz-Price C.C.).

predetermined overcurrent, diverting the whole of the current from one set of current transformers through the relay. Should a fault to earth, or between phases, take place outside the protected zone, the primary current balance is always maintained ; therefore the stability

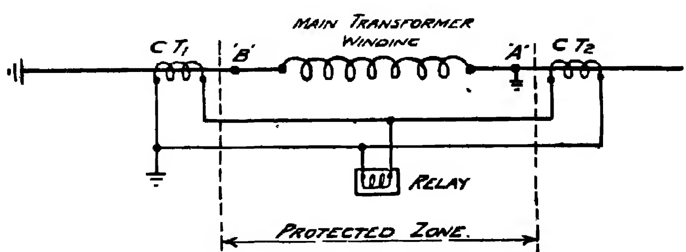


FIG. 245. Circulating current protection (one phase shown).

of the protective system depends only on the balance characteristics of the current transformers. Assuming the ratio of the transformers is 800/5, and a current of 650 amps., then under normal conditions there will be a circulating current through transformer secondaries and pilot wires of $\frac{650}{800} . 5 = 4{\cdot}05$ amps. The relay will carry the difference between the secondary currents of C.T.1 and C.T.2, which in this case will be zero. With an earth fault at " A," Fig. 245, and resistance of fault such that an earth current of 100 amps. flows, then

$$\text{secondary current of C.T.1} = \frac{(650 + 100) . 5}{800} = 4{\cdot}69 \text{ amps.}$$

$$\text{while C.T.2 will be } \frac{650 . 5}{800} = 4{\cdot}07 \quad ,,$$

$$\text{Difference} = \overline{0{\cdot}62} \quad ,,$$

and this will flow through relay coil. A relay designed to operate at $0{\cdot}6$ amp. would therefore operate with a fault current of 100 amps., which is $= \frac{100}{800}$, or $12\frac{1}{2}$ per cent., of the maximum rated current. Now consider a fault at " B ", which is rather unlikely, for there is practically no potential difference between " B " and earth, but in such a case the current through C.T.1 would be equal to the load current minus the earth fault current. With a fault current of 100 amps., the secondary current of C.T.1 will $= \frac{(650 - 100) . 5}{800} = 3.45$ amps. The current through C.T.2 secondary will be $4{\cdot}07$ amps., as before. The difference (relay current) $= 4{\cdot}07 - 3{\cdot}45 = 0{\cdot}62$ amps., as before. A danger of circulating current protection is that a break in a pilot wire will cause relay operation. Through fault currents have caused operation of Merz-Price balanced protection relays but this was due to incorrect initial balancing of the apparatus. The usual causes of inadvertent tripping are : relay tapping points on the pilots not corresponding to the electrical mid-point ; current transformers of inadequate output for the pilot burden at maximum primary current ; and using dissimilar transformers on the star point and busbar connections. A pilot cable of considerable length and laid near main cables will have a voltage induced along its length when the cables are carrying high fault currents, which are returned *via* the earth to the source. Pilot cable breakdown may be caused by current as a result of induced

voltage, and also by ground current traversing the armouring or sheaths. This protection is not fitted to transformers having tap-changing gear, unless one set of transformers have tappings so that their ratios may be changed to correspond with the various changes in main transformer ratio.

When protecting star-star (Figs. 246 and 247) connected transformers on the current balance system, it is necessary that the secondaries of both sets of current transformers be mesh connected before balancing and connecting the two sets of current transformers, over-

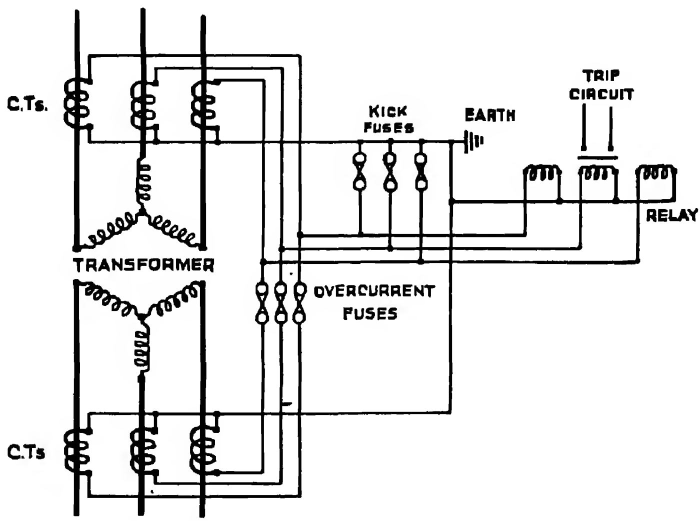


FIG. 246. Star-Star connected transformer.

current fuses should be 75 per cent. larger when star connected current transformers are used. Where a transformer is delta-star, Fig. 248, the current transformer secondaries should be star connected on the primary and delta (or mesh) connected on the secondary to give the correct phase displacement. In cases where one set of current transformers has tappings corresponding with those of the main transformer these should always be altered to the correct range when the tappings of the main transformer are changed. To prevent the relays operating, when switching in a transformer, "kick" fuses short-circuiting the relays should be inserted temporarily and withdrawn immediately the circuit breaker is closed. Overcurrent protection may

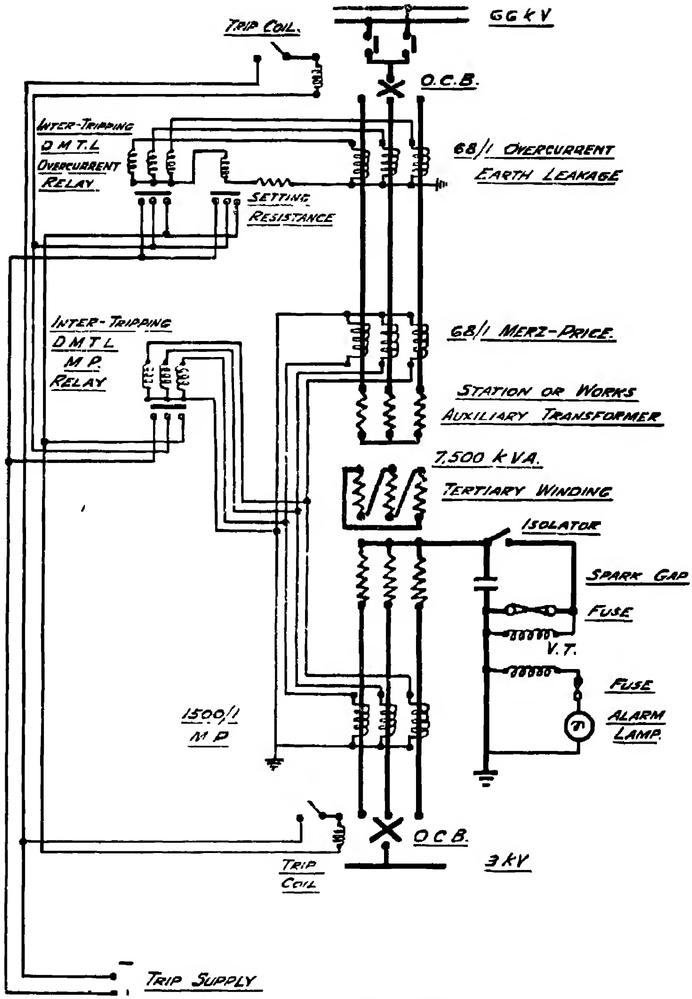


Fig. 247. Star-Star transformer protection.

be obtained by including fuses between the two sets of current transformers.

The "Translay" balanced system, Fig. 249, overcomes the disadvantage of providing tapped overcurrent transformers. Another feature of the "Translay" relay is that it has an inverse time character-

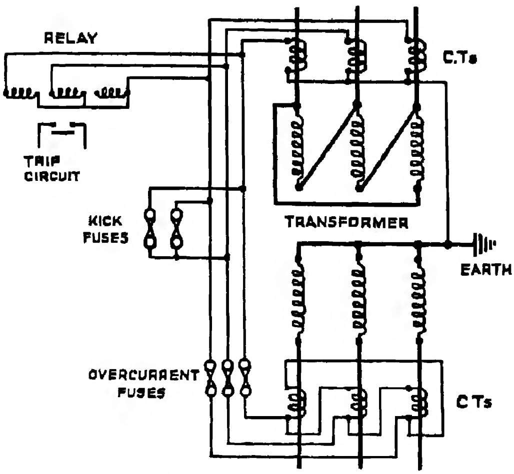


FIG. 248. Delta-Star connected transformer.

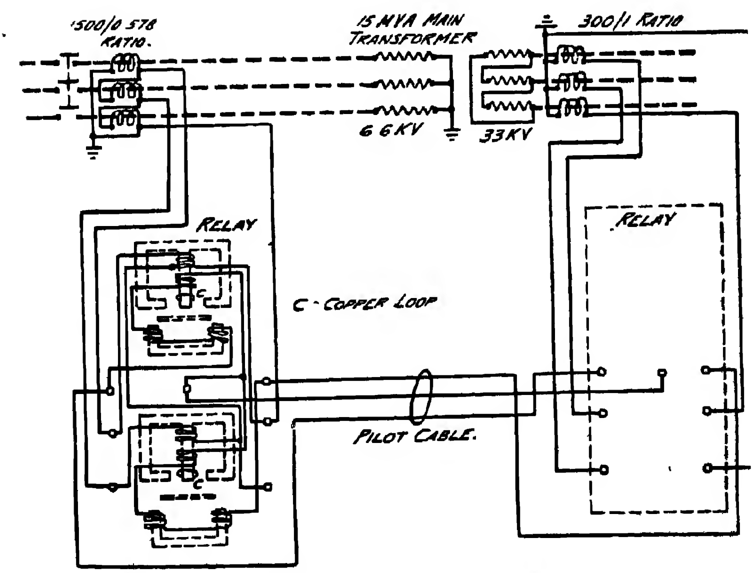


FIG. 249. "Translay" balanced protection.

istic whereby operation is delayed to prevent tripping during the switching-in period of a transformer. With heavy fault currents, the operating time is reduced to 0·25 of a second at full setting, and proportionately lower times at lower settings. Under healthy conditions,

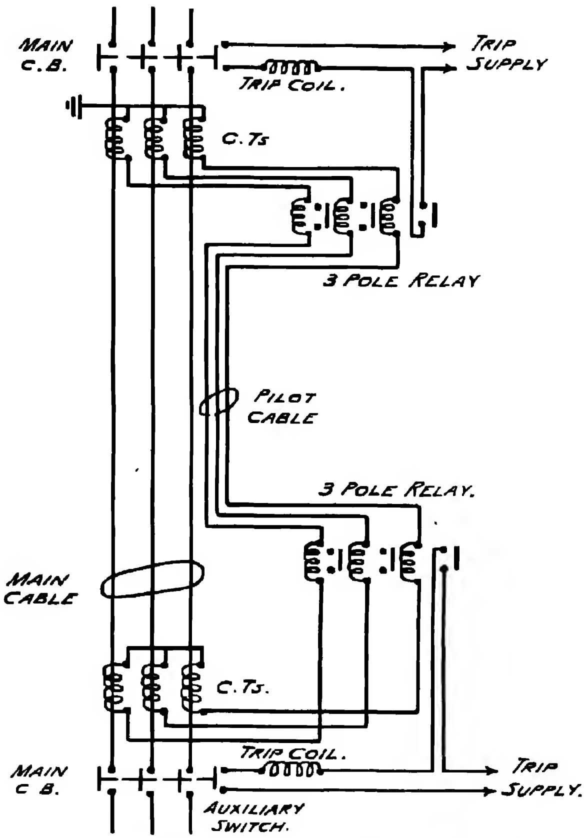


FIG. 250. Merz-Price balanced voltage feeder protection.

the current transformers at opposite ends of the feeder (or transformer) supply equal currents in primary windings of the relays, which induce equal voltages in the secondary windings of the relays, but as these voltages are of opposite polarity no current flows through the operating coils except that due to normal conditions of unbalance of the current transformers and of the main transformer. To compensate

for this, copper loops are fitted which, in addition to counteracting the lack of balance between current transformers, are also arranged to give the relay bias to counteract the effect of any changes in main transformer ratio due to tap-changing. The resulting operating torque depends on the position and nature of the fault in the protected zone, and one element at least of either relay will operate under any fault condition.

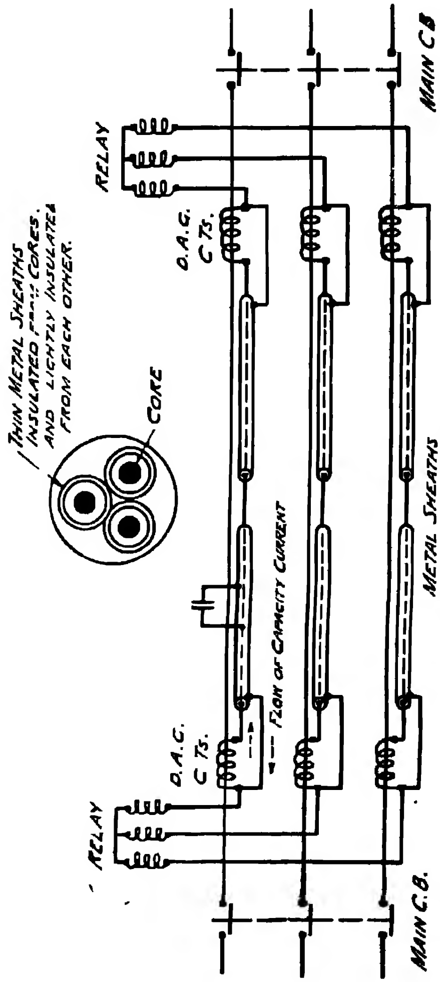


FIG. 251. Sheathed Pilot Wire Feeder Protection.

The Merz-Price balanced voltage system, Fig. 250, has proved satisfactory on short feeders and where through fault currents are small. In feeders over 5 miles long and where fault currents are of the order of 5,000 amps. and over, the capacity currents from core to core of the pilot cable may cause unwanted tripping during fault conditions. To overcome the difficulty which would be experienced owing to the unbalancing effect of capacity currents in the pilot cable, a special compensated pilot cable can be used. A thin metallic sheath is introduced, which surrounds and is insulated from the core and from earth. This sheath is connected in such a manner that the capacity currents do not pass through the relays. The sheaths must be open-circuited at one point ; on short lengths this may be at one end of the

cable, but in the case of longer lengths the screens should be open-circuited at a point approximately midway in the length of the cable. The Sheathed Pilot Wire Protection employs this type of cable, Fig. 251, in which a metal sheath around each pilot wire core avoids the effect of capacity currents by allowing them to flow from the core to the screen, and so by-passing the relay. Such a system can be used on feeders up to about 20 miles long, with through fault currents approaching 10,000 amps.

Split-pilot protection, Fig. 252, is a form of Merz-Price protection and overcomes the capacitance difficulty without the need for a special

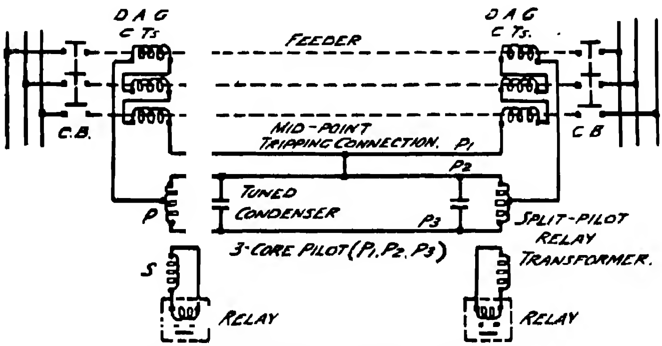


FIG. 252. Split-pilot protection (Reyrolle).

pilot cable. Three current transformers of the air-gap type, each having a different number of secondary turns, are connected in open delta through a three-core pilot cable to a similar set at the other end of the feeder. The two sets of current transformers are connected so that, normally and under through fault conditions, current circulates between them *via* the pilots. The relay transformer secondary winding is connected to a single-pole instantaneous electro-magnetic relay. Under normal and external fault conditions, the currents flowing in pilots P2 and P3 are equal, and no current passes across the mid-point connection, since the two points are normally equipotential. With a fault in the protected zone, the currents generated by the two sets of current transformers become unequal, resulting in unequal currents in pilots P2 and P3, and so causing the relays at each end to operate. To ensure that the protection is not affected by transient disturbances in the network, the relay transformer is tuned with a condenser, so that the relay is unaffected by high-frequency currents.

Feeder Protection. *Comparison between "Translay" and "Split-pilot" protection.*

Feature	Translay	Split-pilot
Compensation for pilot capacity.	Relay inoperative with currents of low leading power factor ; unsuitable for long lines as phase angle varies.	Inherently stable pilot capacity currents ballanced out on split conductor principle.
Compensation for high frequency out-of-balance currents.	Shunting resistance across C.T. Method originated by Reyrolle, but found to be of no practical use. Actual tests on "Translay" relay confirm this.	Tuned relay inoperative at frequency above third harmonic.
Compensation for transformer unbalance.	Obtained by biassing the relay. Percentage bias may have to be high to obtain stability (solid core C.T.'s). C.T.'s must be balanced.	D.A.G. transformers are used which are balanced to within very close limits against a standard. Thus the transformer out of balance is very small.
Operation of Relays if fault is fed at one end only.	At feed in end only.	At both ends.
Time to clear any kind of fault including 0·2 sec. for operation of switch.	0·95–0·3 sec., depending on severity of fault.	0·6–0·25 sec. depending on severity of fault.
Fault settings.	Relay calibrated for 50 per cent. to 85 per cent. for earth faults. The calibration is for negligible lengths of pilots and settings increase with length of line. Phase fault settings are four to eight times earth fault settings.	For lines up to six miles and stability 8,000 amps. Earth fault settings 100/150 amps. Phase fault settings 400/600 amps.
Apparatus required at one end of feeder.	(*a*) Three metering current transformers 5-amp secondaries ratio depends on size of feeder. (*b*) One single or two-pole relay. (*c*) One pilot dividing box.	(*a*) Three D.A.G. current transformers ratio 400/1, 500/1 and 600/1 balanced against standard to fine limits, each set can be used for any feeder. (*b*) One single-pole relay. (*c*) One pilot dividing box containing split-pilot tuned transformer.
Pilot cable.	Ordinary two or three-core.	Ordinary three-core.

Another form of Merz-Price protection is the Solkor, Fig. 253, which is designed to work with ordinary closed-core current transformers. These transformers are connected through different numbers of turns on a saturable summation transformer, so that normally a voltage obtains in the secondary of this transformer. The secondaries of the two summation transformers are connected in opposition, so that no current flows. This method overcomes the difficulty of any unbalancing of the current transformers under heavy through-faults, for under such conditions the two summation transformers become saturated. Normal frequency out-of-balance currents are provided

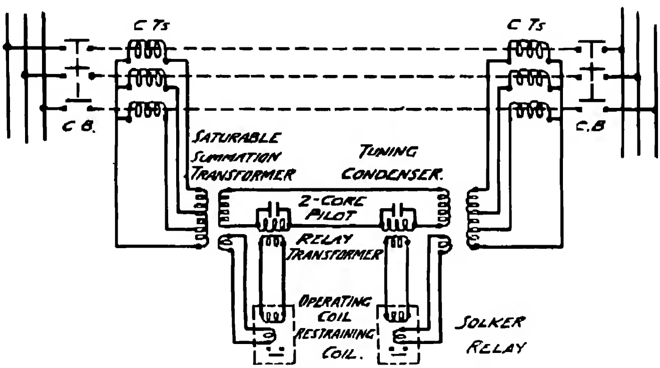


FIG. 253. Solker protection (Reyrolle).

for by the restraining core on the relay, which, in turn, increases the relay setting with the fault current. With a fault in the protected zone, there is a large out-of-balance between the voltages of the summation transformers, which causes current to circulate in the pilots to operate the relays. Such a method is free from pilot capacity currents, as the saturation of the summation transformers maintains the pilot voltage at about 120 volts under fault conditions, and limits the pilot cable current. Comparatively low fault settings are possible. Fig. 254 shows the split conductor type of feeder protection. The operation of this system is dependent upon the balance of current in two similar circuits connected in parallel, should a fault develop on either circuit, the currents become dissimilar and the difference is made to operate the circuit breakers thereby isolating the faulty section. In practice, each core of the feeder is divided into two equal conductors, which are connected at each end to special current transformers having two prim-

ary windings which are wound in opposition and connected to the "split circuits". The single secondary winding is connected to a relay for operating the circuit breaker should a fault arise. Under normal conditions, it will be observed that, as the "split circuits" are carrying equal currents, no current will be induced in the secondary winding of the current transformer, but as soon as dissimilar currents

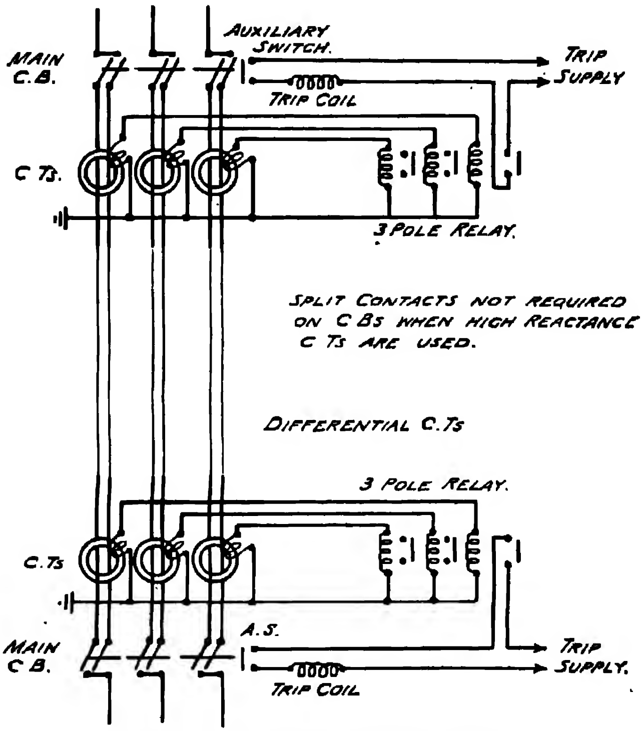


FIG. 254. Split Conductor feeder protection.

flow (due to an earth or other fault) a secondary current passes through the relay and will operate the circuit breakers, thus isolating the line at both ends. For satisfactory operation of this system, it is essential that the two halves of the feeder should have approximately the same impedance values.

Mining Protective Equipment. Figs. 255 and 256 show typical systems, the details of which vary according to the conditions

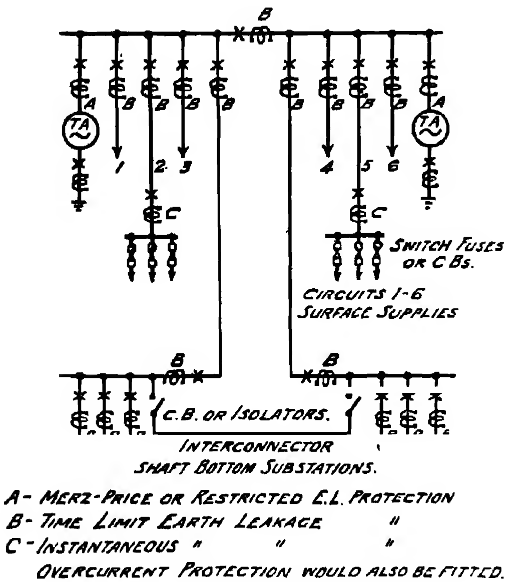


FIG. 255. Typical mining system.

obtaining. For coal-facing working, sub-stations are of a portable nature, and many special features are employed. The modern gate-end switch may have the following features incorporated : overcurrent ; under-voltage ; earth leakage ; earth continuity ; electrical interlock ; remote control ; pilot core ; temporary failure of supply ; visible earth-leakage indicator ; visible shorted pilot indicator ; provision for re-setting earth-leakage and pilot core protective relay.

The overcurrent device should withstand the high current at starting, yet provide normal overcurrent protection. Two-rate dash-pots enable this to be done. The main circuit is controlled by a contactor, and under-voltage is therefore an inherent feature. Any leakage, however small, should operate the relay, and a value of 10 per cent. of full load is usual. The core-balance system is quite suitable, and an alternative is shown in Fig. 257. The earth continuity feature ensures that the motor cannot be energised unless there is a continuous earth connection. This is made possible by a pilot circuit, the current from which is passed through the earth conductor of the trailing cable. The withdrawal of plugs or the mechanical failure of pilot cores in earth circuit will trip the main contactor. The primary object of the earth continuity feature is to ensure a reliable earth connection between the machine protected and the gate-end box, and necessitates a pilot core in the main cable. The electrical interlocks include devices to prevent closing the main circuit until the plugs at both ends of the trailing cable are properly located in their sockets. Remote control enables all power circuits to be opened in the gate-end switch where

working conditions are better. Pilot core protection is used in conjunction with remote control equipment where the gate-end box is controlled by a master switch on the coal-cutter or conveyor. It is designed to guard against a fault on the trailing cable causing a short circuit between the pilot core and the earth core, which would be equivalent to closing the master switch.

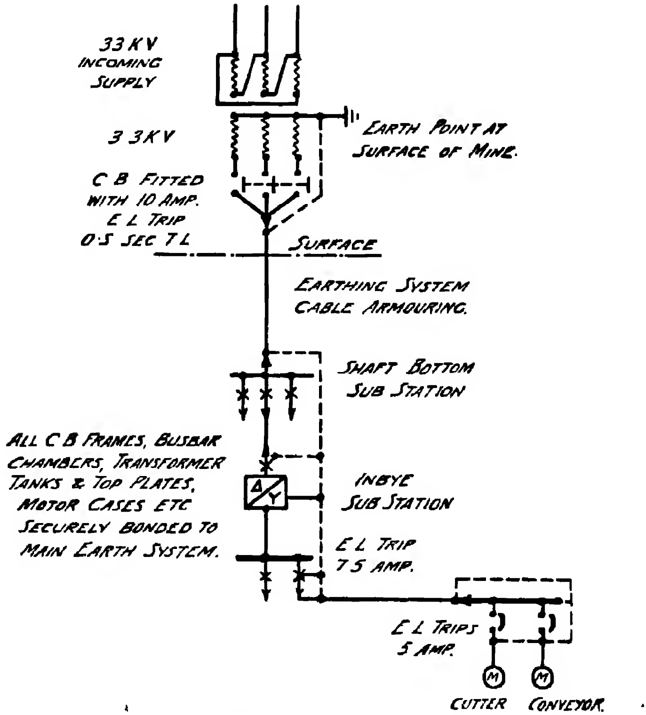


FIG. 256. Earth leakage settings and main earthing.

With remote control equipments provision must also be made to prevent the possibility of the power unit re-starting after a temporary cessation of supply. The operator may omit to return the master switch to the "off" position, and re-starting should be prevented. Operation of the leakage relay allows a red indicator flag to fall, which can be seen through an armour plate glass window, and, in addition, latches itself in the trip position so that the power unit cannot be re-

started until the relay is re-set. This re-setting is done by means of a special key. Leakage tests can be carried out without dismantling the circuit breaker, or withdrawing it from the busbars. The special

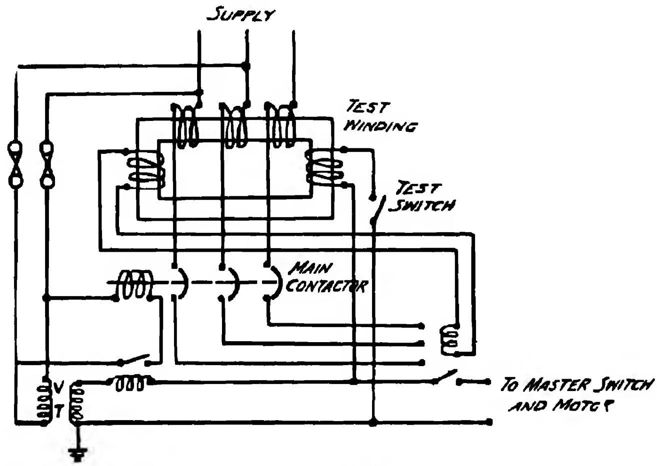


FIG. 257. Earth leakage protection.

key is provided for this purpose and should be in the possession of the engineer-in-charge. It is possible to operate the testing device, and put an electrical test on the leakage trip coil in series with the secondary

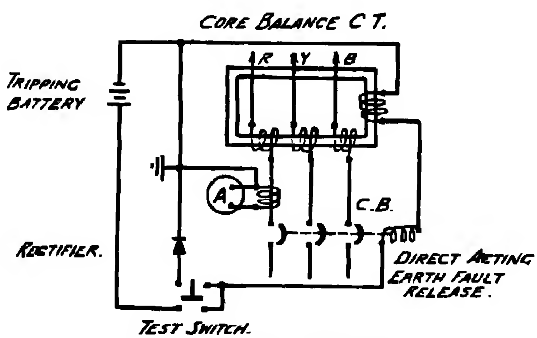


FIG. 258. Earth leakage trip.

circuit of the leakage current transformer, giving an exact reproduction of a leakage fault. Typical diagrams of connections are shown in Figs. 258 and 259.

Fig. 260 illustrates a rectifier in the gate-end box and another at the other end of the cable, mounted in the master switch. The rectifiers are connected back-to-back, so that under normal conditions no load

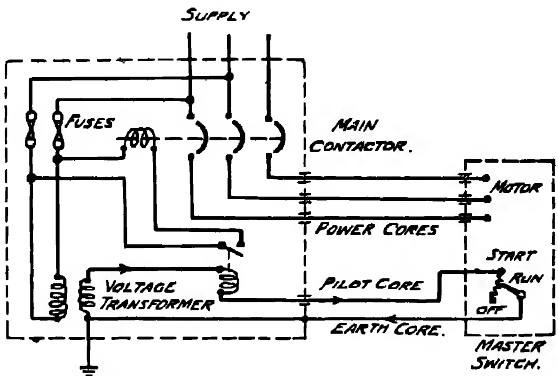


FIG. 259. Earth continuity protection.

current flows into the control relay circuit, R. In the event of a fault between the pilot core and the earth core, the rectifier at the remote end of the cable is shorted, which permits half wave current to flow

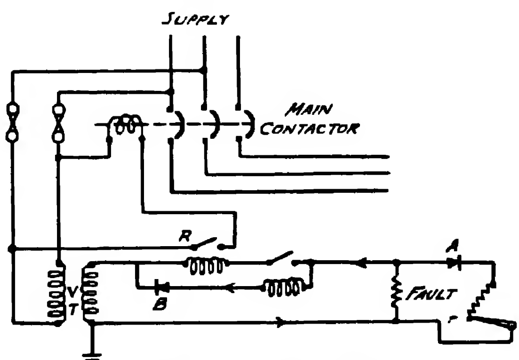


FIG. 260. Pilot core protection.

through the relay, R, and its associated rectifier. Relay R operates to trip the main circuit breaker, and at the same time latches itself in the tripped position and drops a white flag. The pilot core protective device R is re-set by means of the special key provided for the earth leakage device.

Earthing. It is necessary to consider not only the actual connection with earth but the various connections to that point, as a good earth connection is of little value if the standard of bonding throughout the earth system is poor. The advantages of system earthing are :

(1) Persistent "arcing grounds" are eliminated.

(2) Sensitive protective apparatus can be applied.

(3) High-voltage surges to the system are reduced.

(4) Current which flows to earth when a breakdown occurs is limited.

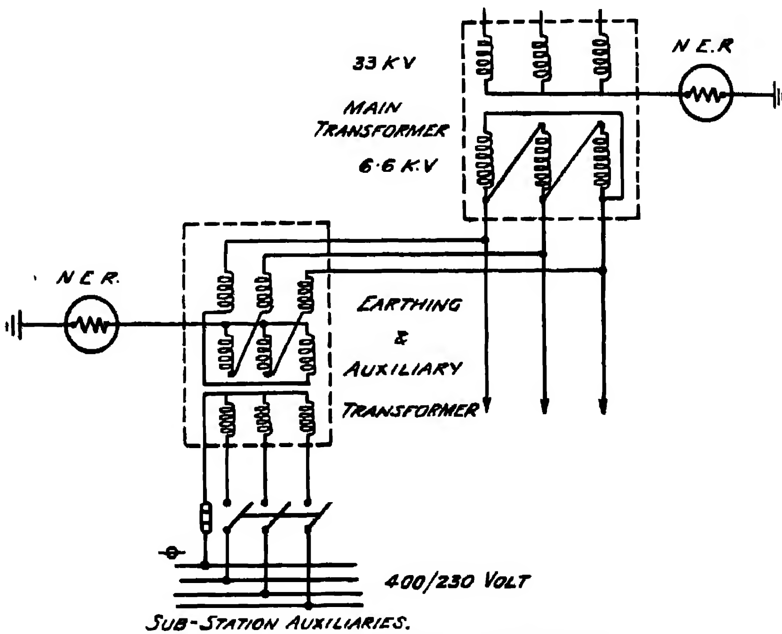


FIG. 261. Main earthing and auxiliary equipment.

A higher-voltage system is earthed chiefly for the protection it affords, whereas a lower-voltage neutral is earthed to reduce possible danger to human life. Where energy is transformed, the Electricity Regulations require that the lower-voltage system should be prevented from becoming charged above its normal voltage by way of leakage or electrostatic induction (capacity effect) from the higher-voltage system. On higher-voltage systems it is usual to earth direct or through a resistance or reactor, *e.g.*, the neutral of a 132 kV system is

earthed through a resistance which limits the maximum earth-fault current and the severity of faults to earth. At the same time, the

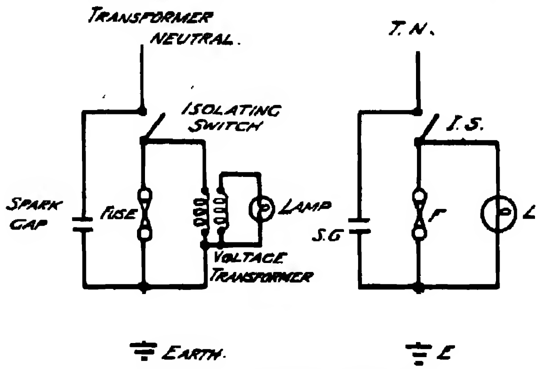


FIG. 262. Earthing arrangements.

resistance also serves to limit the maximum fault current to a value below that which would induce a dangerous voltage in the Post Office

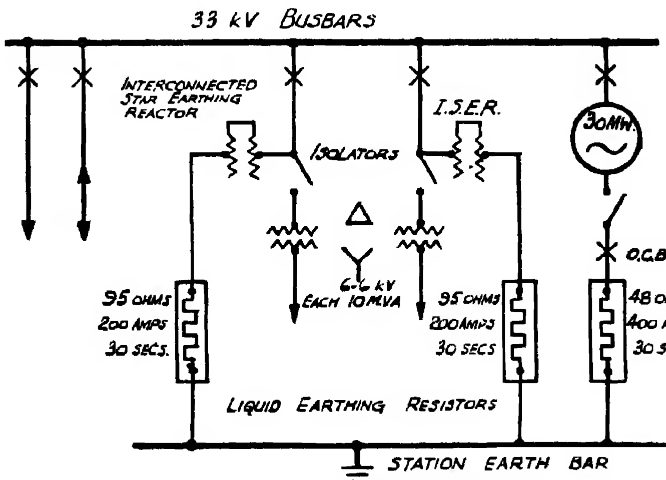


FIG. 263. 33 kV system neutral earthing.

telephone lines in the area. Lower-voltage systems are generally earthed direct. There is no fixed rule for determining the ohmic rating of a neutral resistance, the most important factors to be con-

sidered being the type of protective gear used, and the proportion of transformer or machine windings to be protected against earth faults. The function of the neutral resistance is to limit the fault current, and so protect the plant from abnormal current stress. A large fault current enables the transformer or machine windings to be more adequately protected ; the voltage and transient voltage stress on the system to be reduced ; the margin of safety in fault current over the fault setting of the protective gear to be increased, and the fault to be more readily located. It is necessary to ensure that the restricted earth current is in excess of the highest feeder overcurrent relay setting on the system if overcurrent protection only is fitted and it is desired to protect against earth faults as well as phase faults. If the feeder protective gear embodies earth leakage protection, then a much smaller current could be permitted to flow through the resistance.

Assuming that it is essential to have a fault current of 400 amps. on a 33 kV system to ensure operation of the protective gear, then the ohmic rating of the resistance would be given by,

$$R = \frac{V}{I_e} = \frac{33{,}000}{\sqrt{3} \cdot 400} = 48 \text{ ohms.}$$

V = phase voltage $= \frac{E}{\sqrt{3}}$ where E is the line voltage.

If I = Normal load current,

i = Primary out-of-balance current,

a = Relay setting $= \frac{100\,i}{I}$ per cent.,

I_e = Maximum earth current allowed,

R = Ohmic value of earth resistance,

then percentage of transformer winding unprotected $= \frac{100 \cdot i \cdot R}{V}$,

but $R = \frac{V}{I_e}$ and $i = aI$;

$\therefore$ percentage of winding unprotected $= \frac{100 \cdot a \cdot I}{I_e}$

and „ „ „ protected $= 100\left(1 - \frac{a \cdot I}{I_e}\right)$

$$\text{or} = 100\left(1 - \frac{i}{I_e}\right).$$

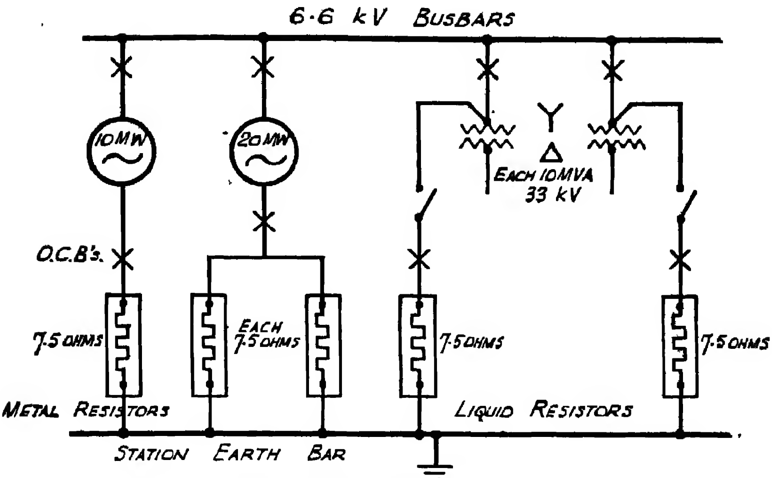


FIG. 264. 6·6 kV system neutral earthing.

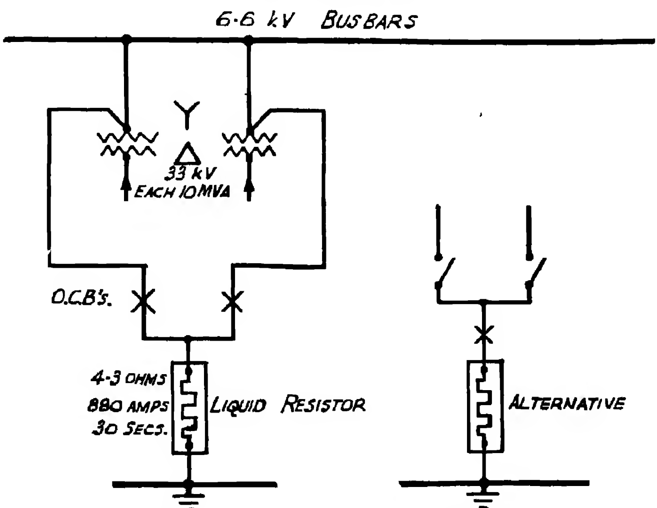


FIG. 265. Main sub-station neutral earthing.

The current ratings of resistances or resistors usually vary from 400 to 2,000 amps., depending on the size and loading of the system, with time ratings of from 15 to 120 seconds. Metallic, carbon powder and liquid types are in use, the latter being the most favoured in recent

years due to its low cost, low surge impedance, and non-inductive feature. Liquid types embodying vertical cylindrical electrodes appear to be preferable to the horizontal plate construction, whilst the current density should be kept within reasonable limits. Convector type liquid resistors are also being used. Liquid resistors have a negative temperature co-efficient (*e.g.*, 60 Ω — 50° F. ; 48 Ω — 60° F. ; 35 Ω — 70° F.), and should, therefore, be of adequate capacity if the danger of

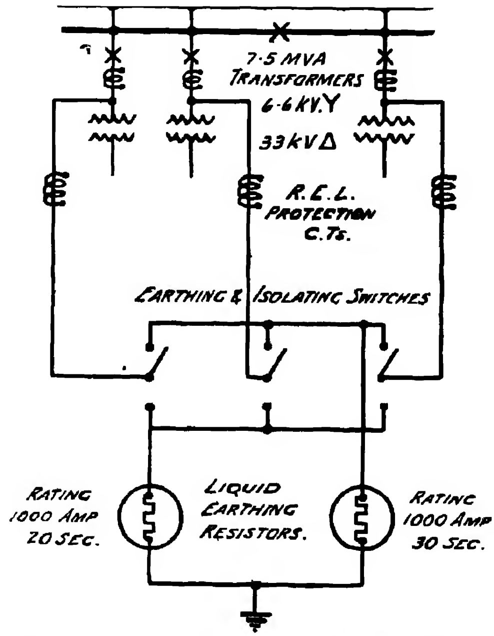


FIG. 266. Sub-station neutral earthing connections.

the liquid boiling away is to be avoided. Heaters are fitted to prevent freezing ; some 6 kW being sufficient. Distilled water is suitable for filling up, soda or other chemical being added, as required, to obtain the desired resistance. A correction curve is provided so that allowance can be made for temperature variations. The resistance can be measured by passing A.C. through the resistor, the voltage drop and current being noted.

The earthing equipment may include a circuit breaker with isolating arrangements, resistor, current transformer for protective gear

or indication purposes, together with neutral cable and connections. Typical arrangements are shown in Figs. 261–268. The neutral circuit breaker is designed to carry the current limited by the resistor, and the rupturing capacity should be adequate ; the short-circuit M.V.A. depending on the method of earthing employed. A non-automatic off-load isolating switch or circuit breaker is employed for sub-station service.

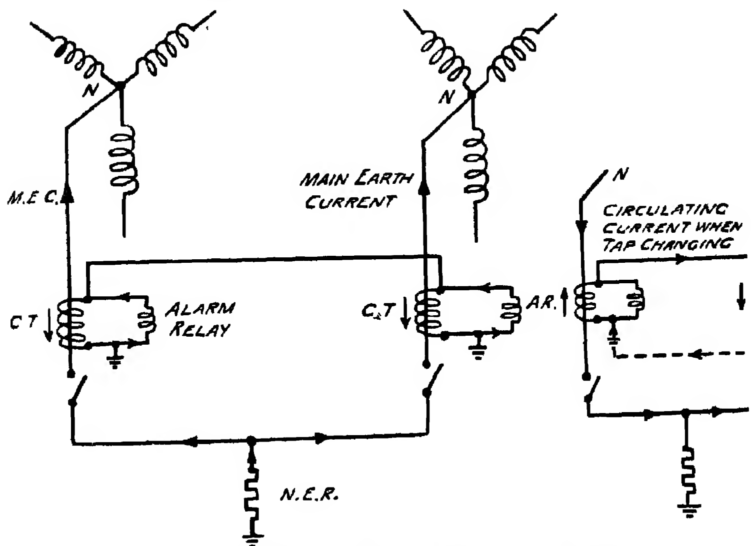


Fig. 267. Method of overcoming alarm relay operation.

Transformer tanks, switchgear, supporting framework, lead-covered cables, etc., must all be effectively earthed. A bare copper earth strip ($1\frac{1}{2}$ in. $\times$ $\frac{3}{16}$ in. section) cleated along the walls of the chamber or the cable trenches will do. Neatness and security are essential, while adequate supporting points are necessary. A group of cables may have the sheaths earthed by means of a bare copper cable sweated to them, providing a sound electrical and mechanical joint is obtained. A specially designed non-magnetic clamp, Fig. 269, makes a sound connection and can be standardised for all sizes of cables. A typical earth bar clamp is shown in Fig. 270.

In mining work, every part of a system should be kept efficiently insulated from earth except that :

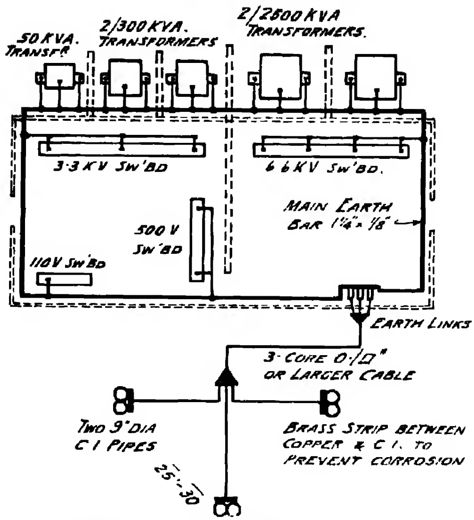
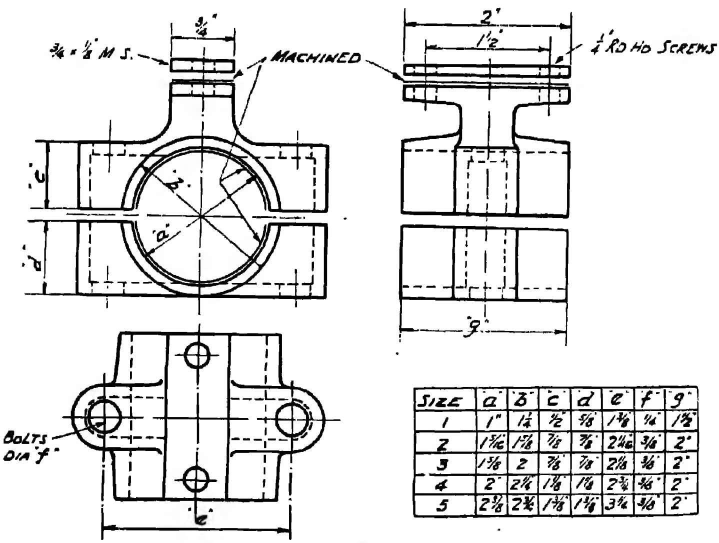


FIG. 268. Typical earthing arrangements for mining surface sub-station.



SIZE	a	b	c	d	e	f	g
1	1"	1¼	½"	⅝	1⅜	¼"	1½"
2	1 5/16	1⅞	⅞	⅞	2 1/16	⅜	2"
3	1⅝	2	⅞	⅞	2⅛	⅜	2"
4	2"	2¼	1⅛	1⅛	2¾	⅜	2"
5	2⅜	2¾	1⅜	1⅜	3¼	⅜	2"

FIG. 269. Cable earthing clamp.

(1) The neutral point of a poly-phase system shall be earthed, and may be earthed at one point only.

(2) The mid-voltage point of any system other than a concentric may be earthed at one point only. Where any point of a system is earthed, it shall be earthed by connection to an earthing system at the surface of the mine.

Regulations forbid earthing at more than one point of one system. The secondary circuit of a transformer (excepting an auto-transformer) being electrically separated from the primary constitutes a separate

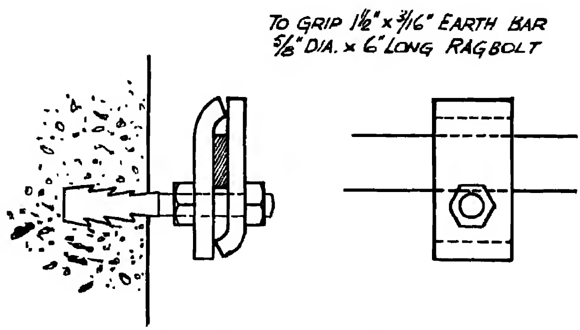


FIG. 270. Earth bar clamp.

system, and may also be earthed. By earthing, it is understood that direct electrical connection to the general mass of earth is made in such a way as will ensure at all times an immediate discharge of electrical energy through the earthing system, or circuit, without danger. Earthing prevents :

(1) Danger from shock in the event of a fault developing.

(2) Open sparking ; fire ; and explosions.

To obtain an efficient earthing system, it is necessary to bond all cable joint boxes and apparatus, and provide suitable earth plates and reliable earth connections at the surface of the mine. All bonds should be as short and straight as possible because they may have to carry high frequency discharges which always choose the path of low impedance.

The connection to earth is made either by a special stranded copper mat, cast iron plate or, alternatively, case iron pipes buried in a bed of coke, if possible below the permanent water level. Cast iron plates about 4 ft. square and from ½ in. to 1 in. thick, strengthened by webs, and 6 in. diameter, ½ in. thick cast iron pipes are used. The plates

should be laid vertically in the soil not less than 6 ft. deep. If the surrounding soil has a tendency to become dry, it is desirable to lay a small water supply to maintain it moist. Precautions should be taken to protect the copper connecters and bonds from corrosion.

A sound earth electrode should possess the following :

(1) Have sufficiently low resistance at all times to pass enough current to operate the protective gear under fault conditions.

(2) Carry the fault current for sufficient time to operate the protective gear without undue increase of resistance.

(3) The voltage gradient on the surface of the ground around the electrode must not be dangerously steep.

(4) It must both stand corrosion from soil and atmosphere.

(5) For certain applications it must have a sufficiently low surge impedance to prevent flash-over from earthed metalwork to insulated conductors when a lightning discharge takes place.

A common electrode is to be preferred rather than having separate earth electrodes for neutral and frame earthing.

With separate earthing a fault to earth from a frame will have to traverse two electrodes in series. If either or both of these are of high resistance or inadequate carrying capacity the fault current may be limited to such an extent that protective gear is inoperative. Furthermore, if the frame earthing is the offender, the potential of the frame, its bond and the electrode may be raised to a dangerous value. This does not obtain with one electrode where all frame earth connections are connected to it and only a small current will flow via the electrode and the risk of high frame potential disappears.

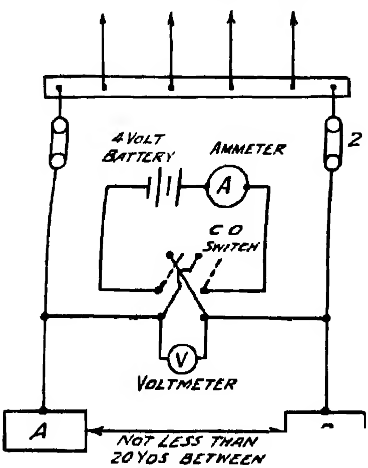


FIG. 271. Earth testing equipment.

Fig. 271 shows a typical diagram of connections for an earthing system with testing equipment. The circuit is so arranged that it is possible to test resistance of the earth connection without interrupting the connections. To make test open link 1 and close switch, thus obtaining a reading between the isolated plate A and the earthing system, including plate B. Reverse the

current flow by changing over the switch position. The lower ammeter reading should be taken, in estimating the value of the earthing resistance, *i.e.*, $R = \frac{E}{I}$, E being 4 volts. When the electrical plant is out of commission, both plates can be isolated by opening links 1 and 2, thereby enabling current readings to be taken between the plates themselves. The Board of Trade requirements for traction purposes are recommended, that is with 4 volts applied across the plates, a current of 2 amps. shall flow between plates spaced not less than 20 yards apart.

A simple method of testing the resistance of an earth plate is to connect one phase to earth through a fuse, and estimate the resistance from the current passing. The higher the resistance of the earth plate, the smaller will be the fuse that can be blown. The continuity of the earth system is most important, and every precaution should be taken to ensure that it is sound in all respects. The sizes of earthing conductors should be based on the maximum earth current flowing and current densities of from 20,000 to 120,000 amps. per sq. in. are usual. Systems have partially lost their main earth connection, and during the period when this prevailed a fault occurred, causing arcing and severe burning of steel fences, cable sheaths, pipes, etc. The resistance of an earthing system affects plant protective gear as will be seen from the following example :

1,000 yards of 500-volt 0·06 cable having a current rating of 60 amps. ; resistance of one core 0·4 ohm ; and resistance of earth circuit 0·8 ohm.

On a 500-volt circuit phase to earth voltage $= \frac{500}{\sqrt{3}} = 285$ volts.

$$\text{Total earth circuit resistance} = 0{\cdot}4 + 0{\cdot}8 = 1{\cdot}2 \text{ ohms.}$$

$$\therefore \text{Leakage current} = \frac{285}{1{\cdot}2} = 240 \text{ amps.}$$

$$\text{Voltage drop on earthing conductor} = I\,R_E = 240\,.\,0{\cdot}8 = 192 \text{ volts.}$$

Assume earth circuit resistance is increased due to poor conditions of earthing conductors to a value of four times the calculated value, *i.e.*, $0{\cdot}8\,.\,4 = 3{\cdot}2$ ohms ; then total earth resistance $= 3{\cdot}2 + 0{\cdot}4 = 3{\cdot}6$ ohms. Corresponding leakage current $= \frac{285}{3{\cdot}6} = 79$ amps.

Voltage drop on earthing conductor $= 79 \,.\, 3{\cdot}2.$
$= 254$

which is dangerous. The power dissipated at this point in the event of an earth fault would be equal to $\left(\frac{285}{3{\cdot}6}\right)^2 . \frac{(3{\cdot}6 - 1{\cdot}2)}{1{,}000} = 15$ kW. This would cause considerable heating to take place and yet the over-current trips may not trip, probably resulting in a fire. The over-current trips on the circuit breakers are set to trip at a value below this figure. Where plain lead-covered cables are run in close trefoil formation (sheaths touching) the sheaths should be bonded about

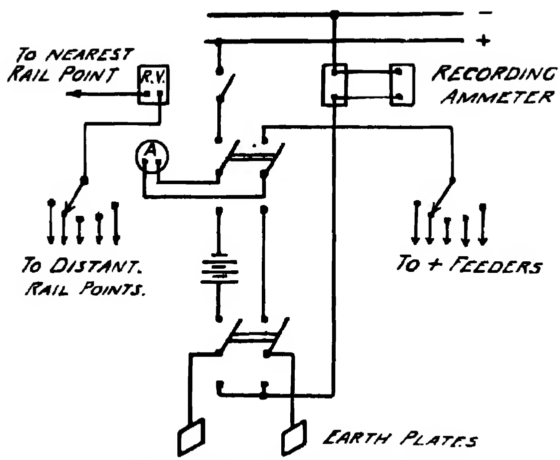


FIG. 272. B.O.T. traction system panel.

every 50 ft. by sweating a shaped lead strip to the three sheaths and connecting it to the main earth bar. This limits the potentials in the sheaths to a safe value above earth potential and also restricts the voltage induced between sheaths. If these precautions are not taken the voltages produced may be sufficiently high to break down the oxide film between the sheaths, thereby causing a current to flow which may result in pitting of the lead. An arc may also form between the sheaths.

Figs 272–274 show D.C. testing connections and Fig. 275 a typical leakage chart.

Busbar Protection. This is required to cover those sections of switchgear not protected by the individual circuit protective apparatus.

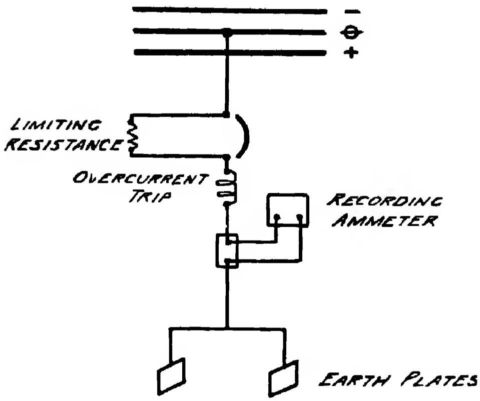


FIG. 273. B.O.T. panel.

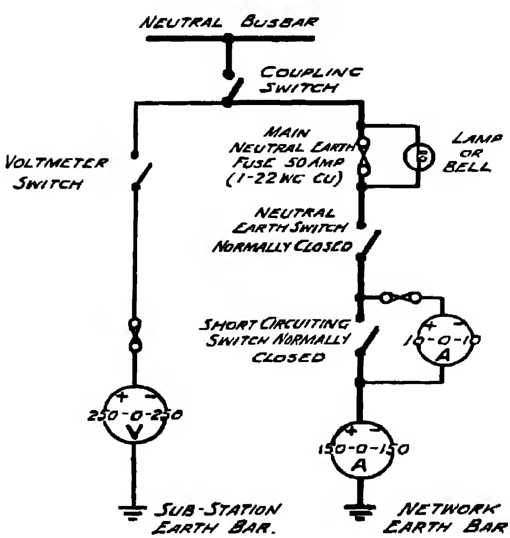


FIG. 274. Earth leakage testing connections.

They include busbars, isolating switches, circuit breakers, and the associated connections ; the assembly being termed the busbar zone.

Leakage to frame protection, which is essentially a particular form of zone protection, has been applied to individual switch and transformer units for many years. A fault in the busbar zone is supplied from all sources of power connected to the busbars, so that the first

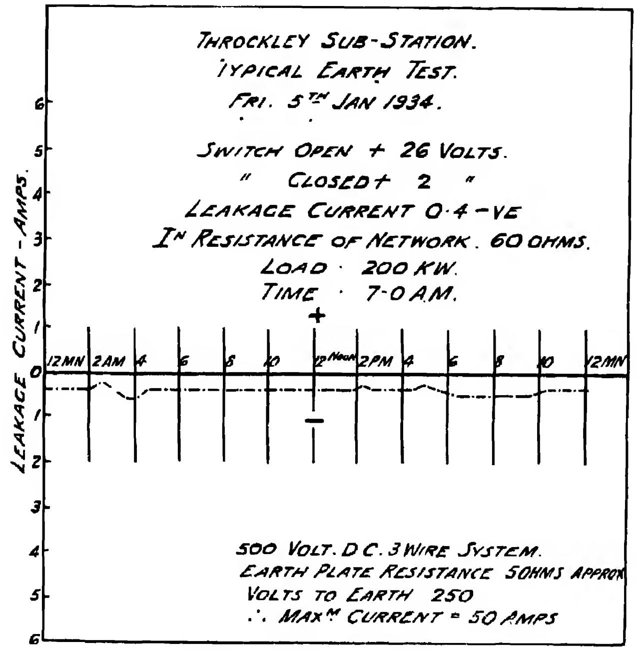


FIG. 275. Daily leakage chart.

requirement is that such supplies should be instantly disconnected. Some degree of protection is afforded by overcurrent protection on the circuits feeding into a busbar fault, but this is not very sensitive. Referring to Regulation 8 of the Factory Act, it would appear that busbar protection is desirable, if not essential, for this regulation states : " Efficient means, suitably located, shall be provided for protecting from excess current every part of a system, as may be necessary to prevent danger." Such protective schemes are designed so that on the occurrence of a fault, or accidental contact by men working on busbar spouts, etc., in the busbar zone special relays

automatically open all circuit breakers through which power can be supplied to the fault. The scheme should be such that any leakage

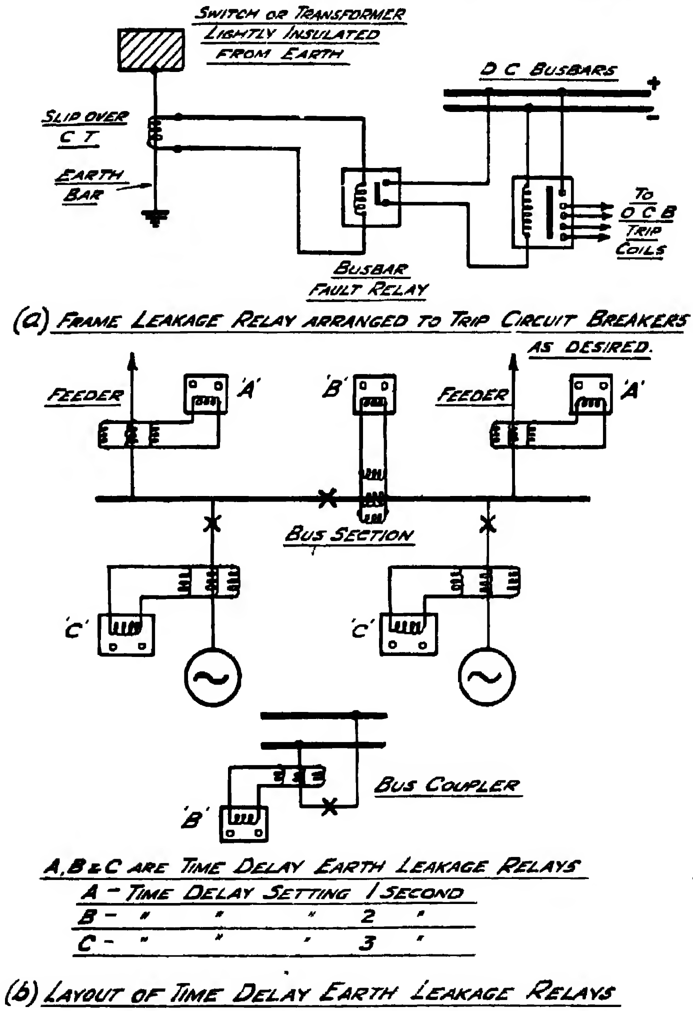


FIG. 276. Busbar protective schemes.

of current from the busbar zone on any section would cause instant disconnection of all supplies to that section.

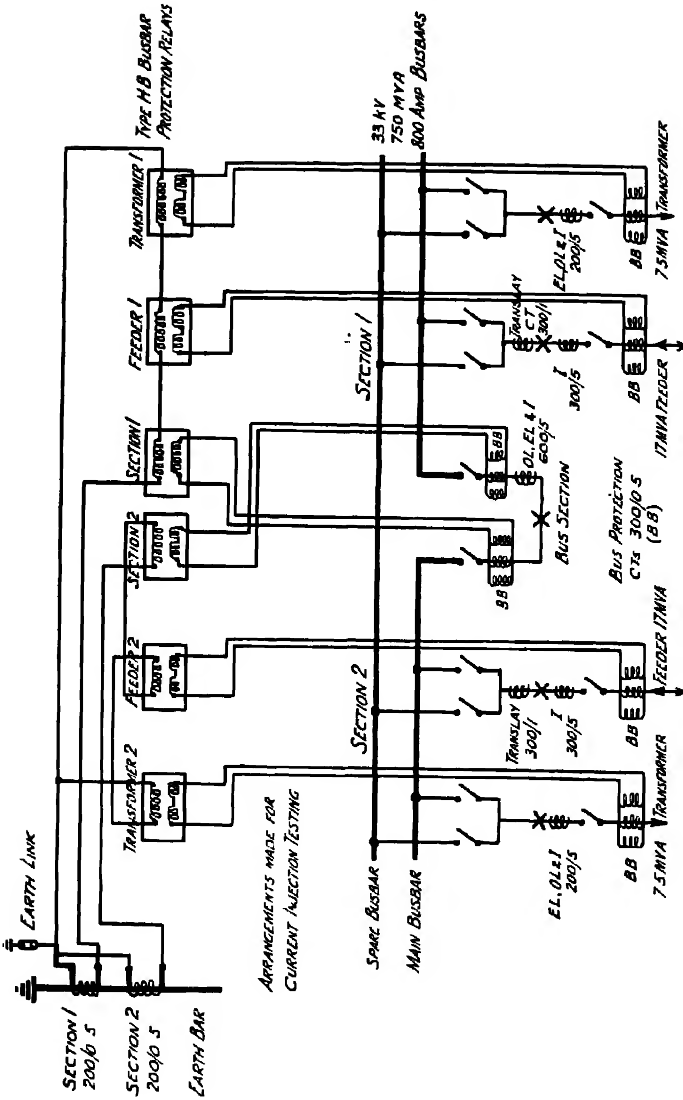


FIG. 277. Busbar protection.

The three principal schemes at the present time are : (1) Circulating current, or differential protection, similar to that used for transformer protection ; (2) Leakage to frame ; (3) Time delay earth leakage relays.

Leakage to frame protection is especially applicable to metal-clad switchgear in which the busbar phases are in separate chambers, since it can only deal with earth faults. It can be adapted to cellular

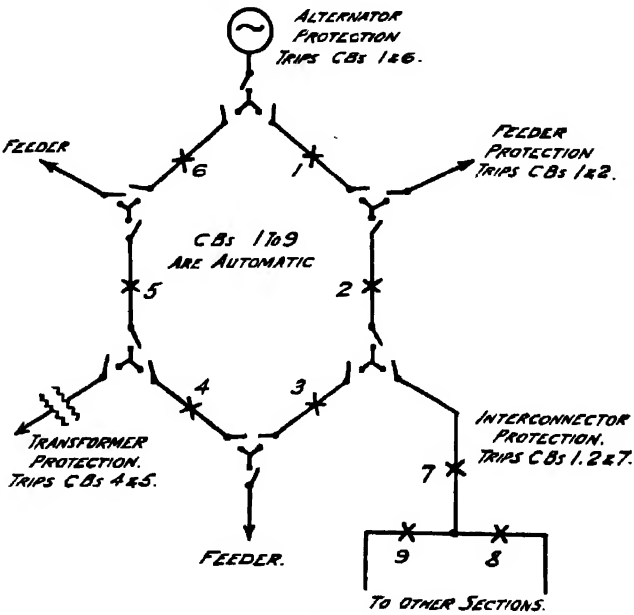


FIG. 278. Mesh protection.

gear, the individual equipments being connected to the earth bar instead of the structure which, if stonework, is already of a semi-insulating nature. For sub-stations without basements reliance is placed on the insulating properties of ½ in. thick asphalt dampcourse. With a reinforced concrete floor frames are mounted on fibre strips and insulated bolts are used. All cables are provided with insulating glands and monthly tests are made to check all insulation. The metal sheathing of cables, and structural steelwork, are lightly insulated from any earthed metal and from the lead sheaths of the incoming and outgoing cables. The frame is bonded to an earthing bar and connected to earth through a conductor which forms the primary of a current

transformer. The secondary of this transformer is connected to an earth fault relay which, in turn, energises a multi-way tripping relay, and, on the occurrence of a fault within the bus-zone, closes the trip

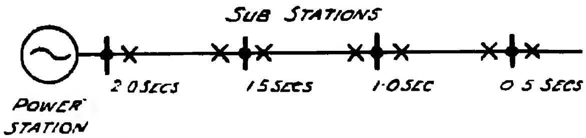


FIG. 279. Radial feeder time grading.

circuits of the circuit breakers connected to the section affected. Operation of the earth fault relay thus causes complete shut-down of perhaps a large portion of a sub-station. The stability of the earth fault relay is, therefore, of prime importance, and inadvertent operation, either electrically or by vibration, may result in a large portion of the plant being disconnected. The possibility of parasitic currents flowing in the earth conductor, and the danger of making temporary earths which short circuit the protective equipment, must also be kept in mind. The D.C. supply to control and indicating circuits should not be earthed. The main cables should be placed central in the current transformer, for the out-of-balance current should be low enough to obtain satisfactory protective balance between current transformers. Figs. 276 and 277 show simplified diagrams of the different schemes.

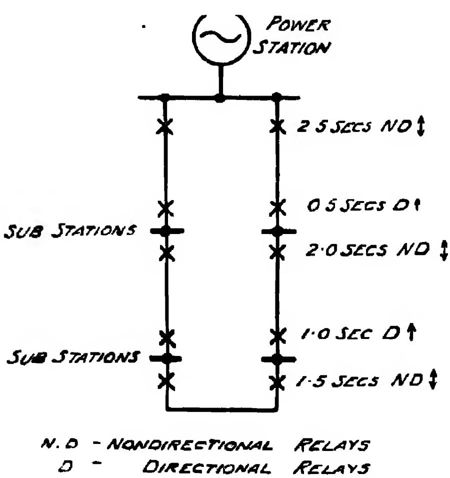
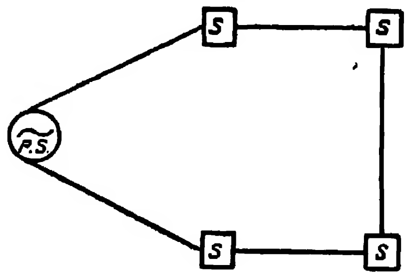


FIG. 280. Ring main time grading.

The problem of busbar protection has been partly solved by dispensing with busbars and grouping the circuits in ring form, or mesh connection. The circuit breakers, Fig. 278, are connected in the ring main, and it is necessary for two to trip to disconnect any circuit automatically.

Typical protection schemes as applied to electrical systems are shown in Figs. 279–283.

Buchholz Protection. This is a special type of protective device, which may be fitted to transformers and reactors. The relay is a float device placed in the connecting pipe between the main tank and the conservator. Normally the closed sight chamber is full of oil, the float



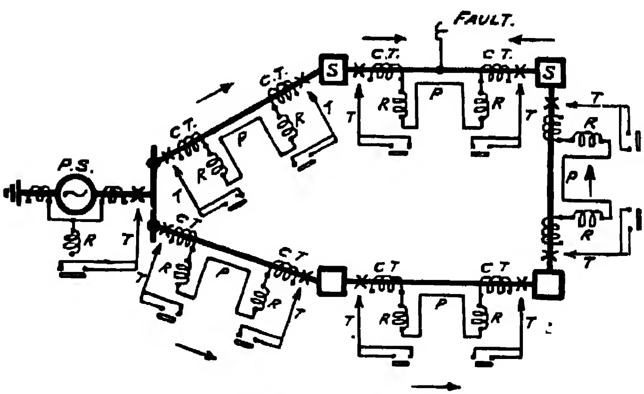


FIG. 281. Ring main protective system.

P—Pilot cables.
R—Merz-Price protective relays. (Circulating current for turbo-alternators, balanced voltage for ring main.)
C.T.—Current transformers.
T—Circuit-breaker tripping circuit.
S—Sub-station.
P.S.—Power station.

being held at the top. In the event of any gas being given off in the transformer due to creepage or breakdown of insulation, short-circuited winding, break in the windings or connections, or circulating current in the core, which give rise to local heating, the bubbles rise

FIG. 282 (*see opposite page*).

Reference	C.T. Ratio	O.C.	U.E.L.	R.E.L.	Remarks
A	800/1	100% 0·6	—	20%	Earth fault 20% . 0·55. Special long delay.
B	800/1	200% 1·0	30% 1·0	—	Translay. 1·0 Phase. 0·4 Earth.
C	300/1	125% 1·0	—	—	Translay. 0·6 P. 0·6 E.
D	1,500/5	125% 2·0 secs.	—	—	Translay. 1,500/0·578. 0·6 P. 0·6 E.
E	300/1	125% 0·85	50% 1·0	—	Translay. 1·6 P. 0·6 E.
F	300/1	—	—	—	Translay. 1·0 P. 0·4 E.
G	600/5	50% 0·35	20% 0·2	—	
H	200/5	150% 0·35	20% 0·2	—	
J	1,000/5	125% 0·35	—	20% 0·5	
K	1,000/5	100% 0·3	—	—	
L	To suit alternator	—	—	—	Merz-Price C.C. and possibly standby overcurrent and neutral alarm.

O.C.—Overcurrent.
U.E.L.—Unrestricted earth leakage.
R.E.L.—Restricted earth leakage.

%—Plug setting.
0·3, etc.—time setting multiplier.

to the sight chamber, so displacing an amount of oil which, if sufficient, allows the float to fall and make contact across an alarm circuit. When such a device is first installed, it is usual to connect for alarm operation only, to prevent inadvertent operation due to air which may be trapped in the transformer tank. It is also possible for this device to operate should there be a sudden abnormal drop in atmospheric temperature, particularly if it coincides with low load on the transformer. Should there be an abnormal oil leakage from the tank, the device will operate before the reduction of oil can have serious consequences. Discrimin-

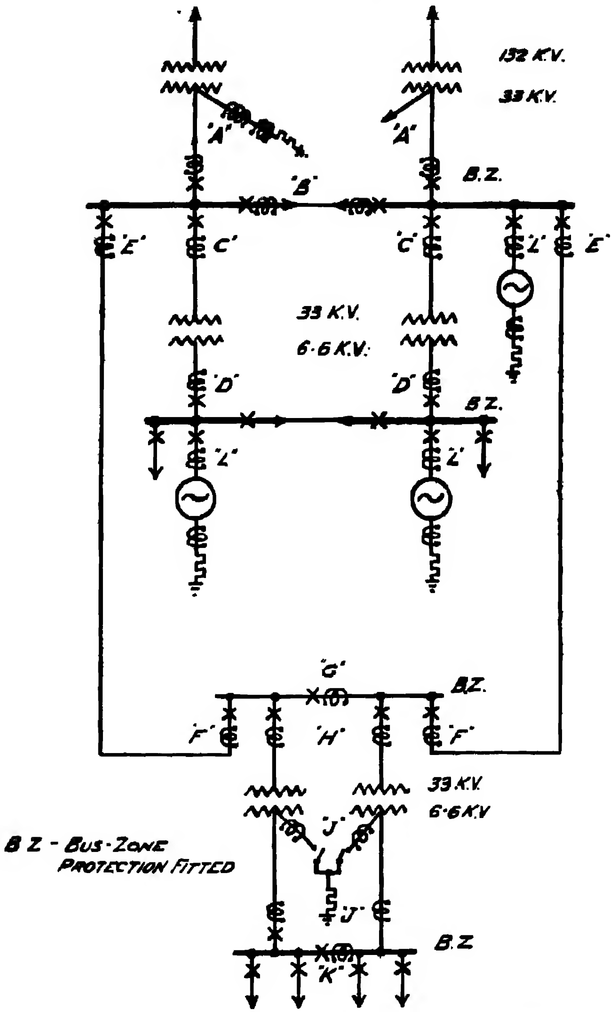


FIG. 282. Typical electrical system with protective gear.

ation between operation due to oil leakage, and operation on electrical faults in the transformer, can be made by inspection of the conservator oil level.

Some types have two floats, Fig. 284, each fitted with a mercury

switch ; the upper float follows the oil level and closes the alarm circuit, whereas the lower float closes the circuit breaker tripping circuit. In one case a circuit breaker tripped out on Buchholz protection caused by a short circuit on the flexible connection to the mercury switches. A pet-cock is fitted to the top of the float chamber to release the collected gases, and if desired a further cock can be fitted to the bottom of the chamber to control a compressed air testing device, which permits of air to be directed against the lower float. This facilitates testing of the electrical circuits for continuity—

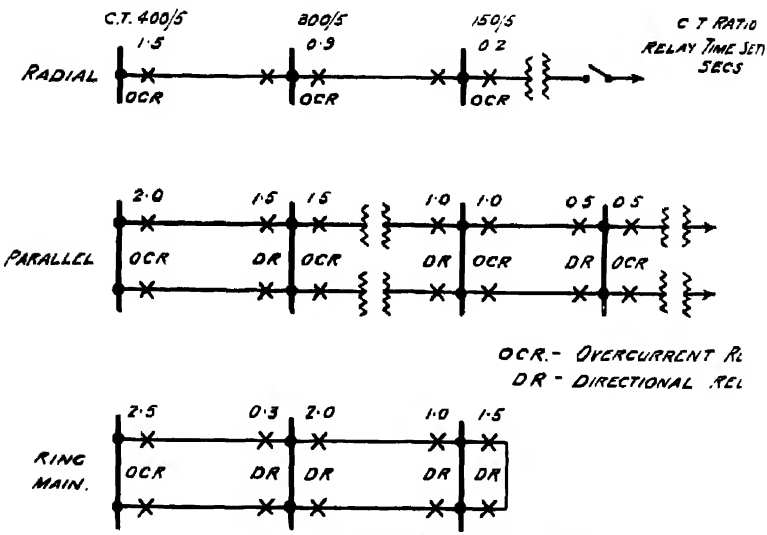


FIG. 283. Typical time grading for supply systems.

a slow release of air operates the alarm float, while quick release causes operation of the tripping float. Some supply authorities arrange to take gas samples and the method of doing this will be appreciated on referring to Fig. 285. The sampling tube is filled with transformer oil by opening both cocks, placing one below the surface of oil in a container, and applying suction to the other, either by mouth or preferably by means of a hand suction pump attached by a rubber connecter. When the sampling tube is completely full and free from air bubbles, the rubber tube is attached and filled with oil by means of a fountain pen filler. The dust cap is removed from the Buchholz release cock and the brass union is screwed on in its place, and filled with

oil using the pen filler. The connections are then tested by holding the sampling tube as shown and opening both cocks, keeping the Buchholz release cock closed. If oil flows continuously from the

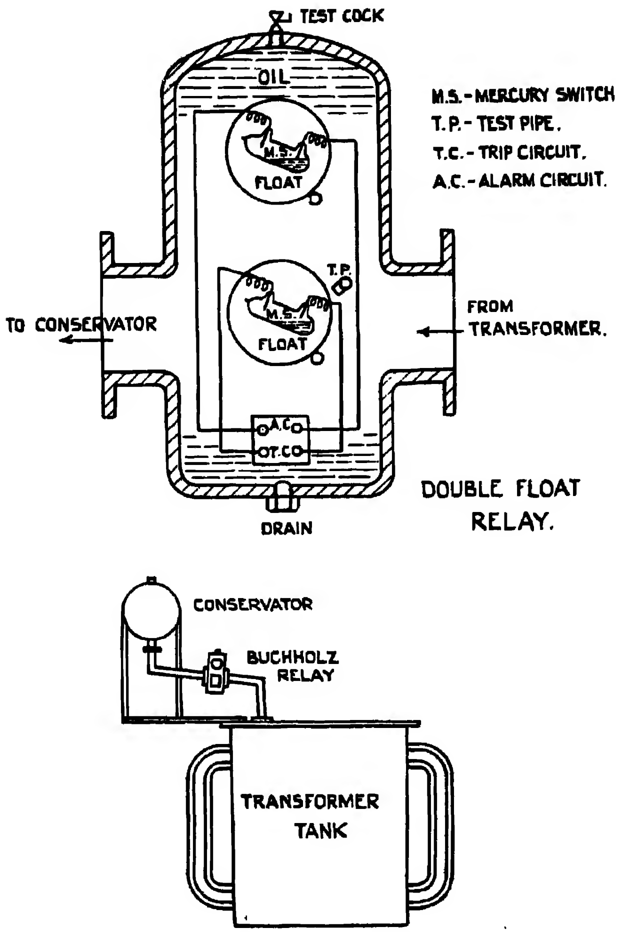


FIG. 284. Buchholz relay.

tube and an air bubble collects at the top, the connections are not air-tight and should be remade. When the connections have been proved air-tight, the release cock on the relay chamber is opened and any

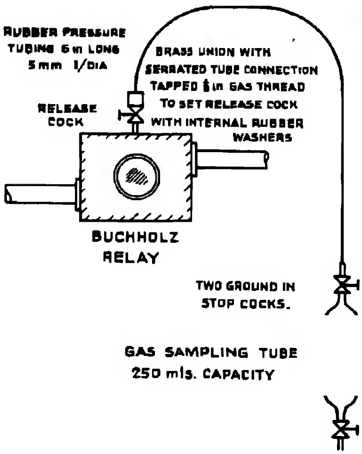


FIG. 285. Gas sampling on Buchholz relay.

gas present is allowed to enter the sampling tube under pressure from the head of oil in the conservator until the tube is almost full or until all gas has been removed from the relay chamber. All cocks are then closed and the rubber tube disconnected from the union and then from the sampling tube. Any gas remaining in the relay chamber should be tested for inflammability by applying a lighted match to the union and opening the release cock slowly. It is advisable to defer the filling of the sampling tube with oil until the sample is being taken, *i.e.*, the filling should be done on site for any increase in temperature may cause the oil to expand with sufficient pressure to break the glass tube. Fig. 286 shows the application of a fault-throwing device using a Buchholz relay. A fault-throwing device can be used when pilot cables are not available. When a Buchholz relay is fitted, it can be arranged to operate simultaneously the local circuit breaker (A) trip coil and the release coil (B) of the fault-throwing switch. The latter is connected between any one phase of the feeder and earth. This affords a second earth fault at full phase voltage and produces adequate fault current to operate the remote

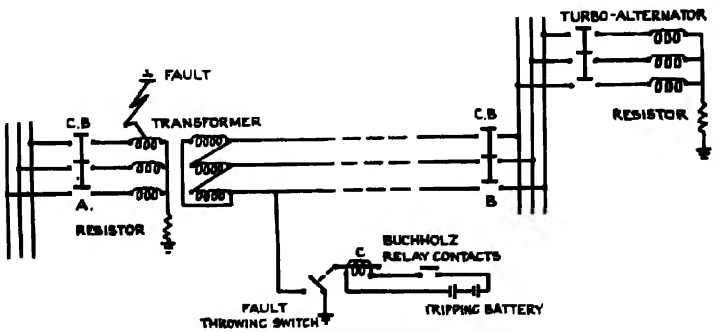


FIG. 286. Fault throwing device.

protective devices fitted to circuit breaker (B). Should the lack of fault current be due to a high neutral resistance, the fault-throwing switch should be connected between any two phases of the feeder.

Converting Plant Protection. Some of the systems of protection are dealt with under the appropriate sections. The protection of motor generators, rotary and motor convertors and frequency changers generally includes overcurrent, earth leakage, and perhaps balanced current schemes, in addition to the more usual starting interlocks, reverse power, polarity, bearing temperature and speed limiting devices, etc. Frequency changers may have each machine protected against internal faults, as well as overcurrent protection, with inter-tripping of both circuit breakers.

Horn Gaps, Surge Absorbers, etc. Devices installed to protect a system against surge voltages include : surge diverters, surge absorbers, co-ordinating gaps and expulsion tubes. Surge diverters of the silicon carbide type have been used on 66 and 33 kV systems and appear to have proved useful. The function of such protective devices is to reduce the wave-front slope, the impulse-wave peak and impulse-wave tail. The device may be included in the overhead line (surge absorber) or branch of the line (horn gap). In both cases the purpose is to dissipate the maximum amount of energy under transient conditions.

The horn gap has been used in connection with overhead lines, but a drawback of this device is its high-impulse ratio, *i.e.*, the ratio of impulse flash-over voltage to the peak value of the normal power-frequency flash-over voltage. It is also unable to rupture heavy current arcs, and a current limiting resistance is included in the line side of the gap. Surge absorbers are designed to operate in series with overhead lines, and protect distribution transformers connected thereto. The absorber consists of an air-cored inductance connected in series with the line and surrounded by, but isolated from, an earthed metallic case. The coil is, in effect, the primary of a transformer, and the earthed metal the secondary. Any impressed impulse voltage is chiefly concentrated across the surge absorber, the surge energy being dissipated in the earthed metal by induction.

The absorber has an appreciable earth capacitance due to it being fixed in a steel casing. A high-frequency surge induces eddy currents in the casing which functions as a short-circuited secondary, thus dissipating the energy which the surge supplied. The absorber distributes the surge voltage uniformly.

Petersen coils, auto-reclosing circuit breakers, earth screens for

sub-stations and earth conductors and overhead lines and terminal cables although serving other purposes come into the category of lightning protective devices. Wood pole lines are often highly insulated in comparison with the insulation level of switchgear and transformers. With no lightning arrestors provided flashovers in the sub-stations may result causing damage to bushings especially on oil circuit breakers of the compound filled type. To prevent flashovers in sub-stations the insulation level of the approach on the last half-mile can be reduced. This can be achieved by earthing cross-arms and providing grading rings on the insulator strings, thus co-ordinating the impulse flashover of the approach lines with the insulation of the switchgear and transformers. Lightning discharges along the wood poles usually cause splintering. Spark gaps fitted to each leg of an H-pole have proved satisfactory in preventing pole damage.

Auto-reclose Breakers. These are used not only to control relatively unimportant spur lines, but also on important long lines (11 kV), for speedy resumption of supply after outage caused by transient fault. One arrangement is to erect the breaker between the links of an H-pole at 6 ft. centres, with line isolators on the adjacent poles or as near thereto as is practicable. Connections from the lines are by bare flexible conductor without any intermediate supports. A platform is provided on the H-pole for inspection and maintenance purposes and is accessible from a guarded ladder. The overcurrent protection comprises current transformers in a compound-filled hood, operating series trip coils with adjustable oil-dashpot settings, the coils and dashpots being inside the main tank (see paper by Fuller and Clarke). The time interval between reclosures is adjustable between 10 and 60 secs., the adjustment being made by a toothed sector operating on to an escapement, the sector position being variable. The adjustment is made externally. The auto-reclose mechanism of one type is operated by means of a falling weight, automatically released by the opening of the circuit breaker. Three closures are available, and the position of the weight shows the number in hand. The mechanism is re-set from the ground level by pulling on a vertical rod which lifts the weight to its re-set position. This rod can be locked in the extreme position, thus locking the breaker open. Internal tank-lowering gear, operated from platform level, is fitted. A further use for such breakers was at a sub-station in low-lying country where flooding was feared. This fear was justified and reinforced concrete posts were used to support the outdoor equipment and the whole of

of the 11-kV equipment was maintained in service during flooding periods.

Protective Gear Irregularities. A feeder circuit breaker operated due to external vibration caused by a cleaner walking across the top of a relay cubicle. A feeder tripped on a through-fault due to incorrect connection of an auxiliary switch and in another case the feeder was accidentally tripped whilst the overcurrent relay was being adjusted.

A transformer circuit breaker tripped on an external fault due to an incorrect neutral connection added after the protective gear had been checked.

In another instance a feeder operated due to an intertrip relay which had not surge proof characteristics, whilst a further example showed that a feeder circuit breaker tripped due to incorrect connection of the earth leakage relay.

Bibliography

E. H. W. BANNER. "The Lightning Protection of Buildings," *The Engineer*, 17th and 24th July, 1942.

B.S.I. "Protection of Structures against Lightning." (C.P.I., 1943.)

J. H. BUCHANAN. "Design, Construction and Testing of Voltage Transformers," *Journal I.E.E.*, Vol. 78, 1936.

T. H. CARR. "Electric Power Stations," Vol. 2. (Chapman & Hall.)

W. CASSON and F. A. BIRCH. "The Management of Protective Gear on Power Supply Systems," *Journal I.E.E.*, Vol. 89, 1942.

P. W. CAVE. "Earthing," *Mining, Electrical and Mechanical Engineer*, October, 1944.

C. J. E. DIXON. "Convector Type Liquid Earthing Resistors," *Electrical Industries*, September, 1944.

J. W. GALLOP and R. H. BOUSFIELD. "Applications and Limitations of the Inverse Time Overload Relay to the Protection of an 11 kV Network," *Journal I.E.E.*, Vol. 70, 1932.

P. J. HIGGS. "An Investigation of Earthing Resistances," *Journal I.E.E.*, Vol. 68, 1930.

M. KAUFMANN and J. W. HODGKISS. "Carrier Current Protection," *Electrical Times*, 9th August, 1945.

C. L. LIPMAN. "Some Recent Advances in the Design of Relays for the Protection of A.C. Systems," *Journal I.E.E.*, Vol. 70, 1932.

R. T. LYTHALL. "Excess Current Protection by H.R.C. Fuses on M.V. Circuits," *Journal I.E.E.*, Vol. 92, Part II, No. 29.

D. MORGAN and H. G. TAYLOR. "The Resistance of Earth Electrodes," *Journal I.E.E.*, Vol. 72.

PARKER. "The Application of Electricity to Quarries," *Mining, Electrical and Mechanical Engineer*, March and April, 1945.

T. W. ROSS and C. RYDER. "High-Speed Protection as an Aid to Maintaining Electric Service following Short-Circuits," *Journal I.E.E.*, Vol. 83, 1938.

A. G. SHREEVE and P. J. SHIPTON. "Excess Current Protection by Overcurrent Relays on M.V. Circuits," *Journal I.E.E.*, Vol. 92, Part II, No. 29.

J. G. WELLINGS and C. G. MAYO. "Instrument Transformers," *Journal I.E.E.*, Vol. 68, 1930.

J. G. WELLINGS and OTHERS. "Capacitor Voltage Transformers," *Journal I.E.E.*, Vol. 79, 1936.

——. "Induction Relay Testing," *Electrical Review*, 31st May, 1946.

CHAPTER IX

TECHNICAL CONSIDERATIONS AND CALCULATIONS

Short-circuit Calculations. When considering percentage values, it is necessary to bring all values to an equivalent kVA or M.V.A. basis.

Consider fault at " A " (Fig. 287), neglecting resistance of alternator.

Short-circuit kVA (R.M.S.) $= \frac{15 \cdot 1{,}000}{0 \cdot 8} \cdot \frac{100}{12 \cdot 5}$

$= 150{,}000$

Reactance on 15,000 kVA basis $= 12 \cdot 5 \cdot \frac{15 \cdot 1{,}000}{0 \cdot 8 \cdot 15{,}000}$

$= 15 \cdot 7$ per cent.

Consider fault at " B."

Full load O/H line current $= \frac{15{,}000 \cdot 1{,}000}{\sqrt{3} \cdot 33{,}000}$

$= 262$ amps.

Per cent. resistance of line $= \frac{I \cdot R}{E_N} \cdot 100$

$= \frac{262 \cdot 4 \cdot 100 \cdot \sqrt{3}}{33{,}000}$

$= 5 \cdot 5$ per cent.

Per cent. reactance of line $\frac{I \cdot X}{E_N}$

$= \frac{262 \cdot 10 \cdot 100 \cdot \sqrt{3}}{33{,}000}$

$= 13 \cdot 8$ per cent.

Total per cent. resistance to " B " $= 5 \cdot 5 + 1 = 6 \cdot 5$ per cent.

" " " reactance " " $= 15 \cdot 7 + 13 \cdot 8 + 5 = 34 \cdot 5$ per cent.

" " " impedance " " $= \sqrt{6 \cdot 5^2 + 34 \cdot 5^2} = 35$ per cent.

$\therefore$ **Short-circuit kVA at " B "** $= 15{,}000 \cdot \dfrac{100}{35}$

$= 43{,}000$

Consider fault at " C."

200 kVA transformer (15,000 kVA basis) $1 \cdot \dfrac{15{,}000}{200} =$ 75 per cent. resistance.

$5 \cdot \dfrac{15{,}000}{200} =$ 375 per cent. reactance.

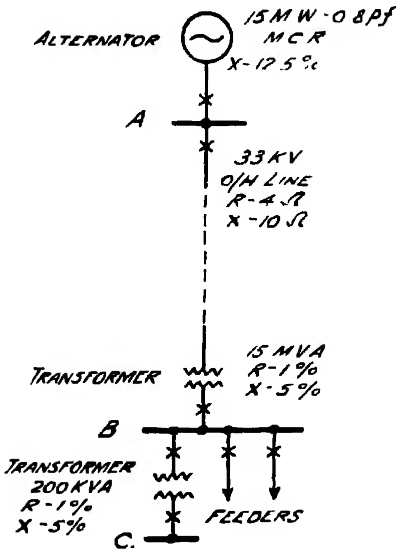


FIG. 287.

Total per cent. resistance to " C " $= 5 \cdot 5 + 1 + 75 = 81 \cdot 5$ per cent.

" " " reactance " $= 15 \cdot 7 + 13 \cdot 8 + 5 + 375 = 409 \cdot 5$ per cent.

" " " impedance " $= \sqrt{81 \cdot 5^2 + 409 \cdot 5^2} = 410$ per cent.

$\therefore$ **Short-circuit kVA at " C "** $= 15{,}000 \cdot \dfrac{100}{410}$

$= 3{,}360$

As check :

Fault kVA at " B " $= 43{,}000$ as before.

Equivalent reactance — Transformer, 5 per cent. on 200 kVA

$= 25 \cdot \dfrac{1{,}000}{43{,}000} = 0 \cdot 58$ ohm. — or $= 25$ per cent. on 1,000 kVA

Total per cent. reactance at " C " $= 5 + 0 \cdot 58$
$= 5 \cdot 58$

$\therefore$ Short-circuit kVA at " C " $= 200 \cdot \dfrac{100}{5 \cdot 58}$

$= 3{,}600$ kVA approximately.

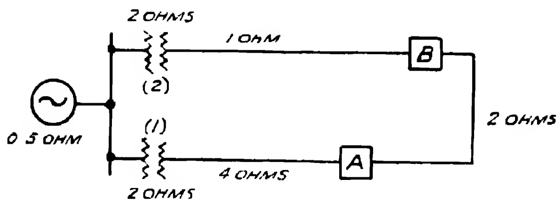


FIG. 288.

In Fig. 288 impedances of routes (1) and (2) in parallel :

(1)	(2)
2 ohms.	2 ohms.
4 „	1 ohm.
2 „	
8	3

In parallel $\frac{1}{8} + \frac{1}{3}$

$$\frac{3+8}{24} = \frac{11}{24} \text{ or } Z = \frac{24}{11} = 2 \cdot 18 \text{ ohms.}$$

Total impedance to " B " $= 2 \cdot 18 + 0 \cdot 5 = 2 \cdot 68$ ohms.

Short-circuit current at "B" $= E/Z = \dfrac{33{,}000}{\sqrt{3} \, . \, 2 \cdot 68} = 7{,}100$ amps.

$= 405{,}000$ kVA.

To find fault kVA at " A."

(1)	(2)
2 ohms.	2 ohms.
4 ,,	1 ohm.
	2 ohms.
6	5

In parallel

$$Z = \frac{6 \,.\, 5}{6 + 5} = \frac{30}{11} = 2{\cdot}73 \text{ ohms.}$$

Total impedance to " A " $= 2{\cdot}73 + 0{\cdot}5 = 3{\cdot}23$ ohms.

Short-circuit current at " A " $= E/Z = \dfrac{33{,}000}{\sqrt{3} \,.\, 3{\cdot}23} = 5{,}900$ amps.

$= 336{,}000$ kVA.

If the power factor of the short circuit is required, then the problem is more difficult, as the resistance and reactance must be considered as a complex quantity, involving operator *j*, as shown in the following example (Fig. 289).

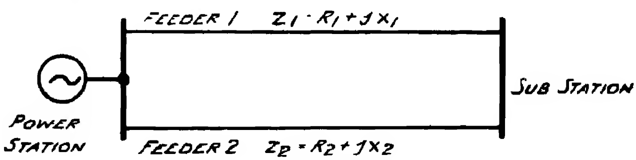


FIG. 289.

Equivalent impedance of the two routes in parallel :

$$Z = \frac{Z1 \,.\, Z2}{Z1 + Z2} = \frac{(R1 + jX1) \quad (R2 + jX2)}{(R1 + jX1) + (R2 + jX2)} = R + jX$$

$$= \sqrt{(R^2 + X^2)}$$

$$\text{Short-circuit current} = \frac{E}{Z} = \frac{E}{\sqrt{3} \,.\, (R^2 + X^2)}$$

$$\text{Power factor of short-circuit current} = \frac{R}{Z} = \frac{R}{\sqrt{(R^2 + X^2)}}$$

When dealing with short-circuit calculations and distribution problems generally which involve different voltages, it is necessary

to bring all resistances, reactances and impedances to an equivalent basis for one particular voltage. The following example indicates the procedure.

A 30,000 kVA 33/6·6 kV transformer has an impedance of 9 per cent. ; calculate the values of impedance per phase at 33 and 6·6 kV.

Full load current I_{FL} $= \dfrac{30{,}000 \, . \, 1{,}000}{\sqrt{3} \, . \, 33{,}000} = 525$ amps.

Impedance per phase $= Z = \dfrac{E}{I} = \dfrac{33{,}000 \, . \, 0{\cdot}9}{\sqrt{3} \, . \, 525}$

$= 3{\cdot}26$ ohms.

Equivalent impedance at 6·6 kV $= \dfrac{3{\cdot}26}{\left(\dfrac{33{,}000}{6{,}600}\right)^2}$

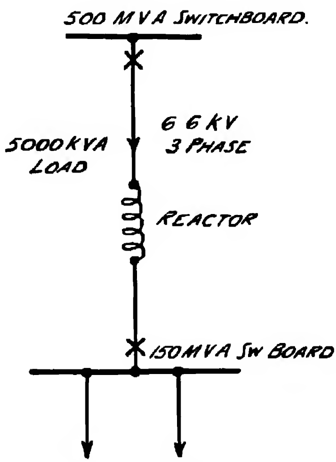


FIG. 290.

Fig. 290 shows the application of a current limiting reactance in a switchgear layout. The load to be transferred is 5,000 kVA, and the system voltage is 6,600 volts ; rupturing capacity of proposed switchgear is 150 M.V.A.

Full load current $I_{FL} = \dfrac{5{,}000 \, . \, 1{,}000}{\sqrt{3} \, . \, 6{,}600} = 440$ amps.

It is necessary to keep within the assigned rupturing capacity of the switchgear, and 100 M.V.A. is assumed.

Equivalent reactance on incoming side is :

10 per cent. on 500,000 kVA = 50,000 kVA.

$$10 \cdot \frac{5{,}000}{50{,}000} = 1 \text{ per cent.}$$

$$I_{SC} = \frac{150{,}000 \cdot 1{,}000}{\sqrt{3} \cdot 6{,}600} = 13{,}200 \text{ amps.}$$

$$X \text{ per phase} = \frac{E}{\sqrt{3}\, I_{SC}} = \frac{6{,}600}{\sqrt{3} \cdot 13{,}200} = 0{\cdot}29 \text{ ohm. (say, } 0{\cdot}3)$$

$$I\,X \text{ drop} = 440 \cdot 0{\cdot}3 = 132 \text{ volts.}$$

$$\text{Reactance} = \frac{132 \cdot \sqrt{3}}{6{,}600} \cdot 100 = 3{\cdot}46 \text{ per cent.}$$

Total circuit reactance (excluding cables) = $1 + 3{\cdot}46$

= $4{\cdot}46$ per cent.,

say $4{\cdot}5$ per cent.

$$\text{kVA rating} = \frac{I_{FL}{}^2 \cdot X}{1{,}000} \text{ single-phase.}$$

$$\text{or} = \frac{3 \cdot I_{FL}{}^2 \cdot X}{1{,}000} \text{ three-phase.}$$

$$= \frac{3 \cdot 440^2 \cdot 0{\cdot}3}{1{,}000} = 175 \text{ kVA.}$$

or, alternatively, $3{\cdot}5$ on 5,000 kVA = 175 kVA.

$$\text{Fault kVA} = 5{,}000 \cdot \frac{100}{4{\cdot}5} = 110{,}000, \text{ which is satisfactory.}$$

A short circuit on all three phases at the end of a 60 M.V.A., 132 kV line, 50 miles long, the line being supplied by a 60 M.V.A. alternator through a 60 M.V.A. transformer.

Impedance of alternator $= 0{\cdot}4 + 15j$

„ „ transformer $= 0{\cdot}7 + 8j$

„ „ line $= 3{\cdot}6 + 12j$

Total impedance, $Z = 4{\cdot}7 + 35j$

$$Z = \sqrt{4{\cdot}7^2 + 35^2} = 35{\cdot}3$$

$\therefore$ short circuit kVA at the point of short

$$\text{is } \frac{60{,}000 \,.\, 100}{35 \cdot 3} = 170{,}000$$

$$\text{If resistance is neglected} = \frac{60{,}000 \,.\, 100}{35} = 171{,}500$$

Where subsidiary loops have to be considered, it is necessary to change a delta system to a star system or *vice versa* (Fig. 291).

Delta to Star.

$$A1 = \frac{B1 \,.\, B3}{B1 + B2 + B3}$$

$$A2 = \frac{B1 \,.\, B2}{B1 + B2 + B3}$$

$$A3 = \frac{B2 \,.\, B3}{B1 + B2 + B3}$$

Star to Delta.

$$B1 = \frac{A1 \,.\, A2 + A1 \,.\, A3 + A2 \,.\, A3}{A3}$$

$$B2 = \frac{A1 \,.\, A2 + A1 \,.\, A3 + A2 \,.\, A3}{A1}$$

$$B3 = \frac{A1 \,.\, A2 + A1 \,.\, A3 + A2 \,.\, A3}{A2}$$

The estimation of the equivalent reactance where different voltages obtain, is based on the following :

$$\frac{E_2}{E_1} = \frac{T_2}{T_1} = \frac{I_1}{I_2}$$

Where E = voltage.
T = turns.
I = current.

now the reactance $X_1 = \dfrac{E_1}{I_1}$ and $X_2 = \dfrac{E_2}{I_2}$

$\therefore I_1 = \dfrac{E_1}{X_1}$ and $I_2 = \dfrac{E_2}{X_2}$.

Substituting, we get :

$$\frac{E_2}{E_1} = \frac{\left(\dfrac{E_1}{X_1}\right)}{\left(\dfrac{E_2}{X_2}\right)} \text{ or } \frac{E_2^2}{E_1^2} = \frac{X_1}{X_2}$$

$$\therefore \qquad X_1 = X_2\left(\frac{E_2}{E_1}\right)^2$$

and
$$X_2 = X_1\left(\frac{E_2}{E_1}\right)^2 \text{ or } \frac{X_1}{\left(\frac{E_1}{E_2}\right)^2}$$

The same method also applies to resistances and impedances.

A phase to neutral short gives the most severe condition. When the short is symmetrical or between phases, after an interval of 0·1 second the equivalent reactance of the circuit will have been reduced to a figure which is almost equal to the percentage reactance of the circuit,

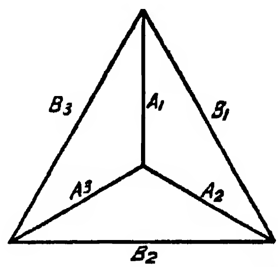


FIG. 291. Equivalent impedances.

i.e., the transient reactance of the alternator plus any external reactance in the circuit.

The apparent reactance of an alternator under steady state conditions is known as the synchronous reactance. When estimating short-circuit conditions it is the transient reactance of the alternator which has to be considered and total asymmetry of the short-circuit current wave is assumed to cover worst possible conditions.

Decrement factors expressed as ratio of r.m.s. short-circuit current to full load current are used but very little error is introduced by neglecting these and calculating all short-circuit figures from the transient reactance of the alternator plus the reactance of any external plant, cables, etc., and ignoring resistance.

Transmission Calculations. Figs. 292–294 show the vector diagrams for the conditions likely to be met in practice.

With unity power factor $E = \sqrt{(V + 2\,IR)^2 + (2IX)^2}$

,, lagging ,, $E = \sqrt{(V \cos \phi + 2IR)^2 + (V \sin \phi + 2IX)^2}$

,, leading ,, ,, $E = \sqrt{(V \cos \phi + 2IR)^2 + (V \sin \phi - 2IX)^2}$

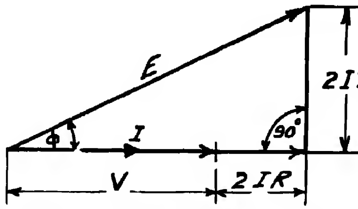


Fig. 292. Vector diagram of transmission line (Unity Power Factor).

or by approximate method

$$E = V + \text{Voltage drop.}$$
$$= V + (2IR \cos \phi + 2IX \sin \phi) - \text{if leading p.f.}$$

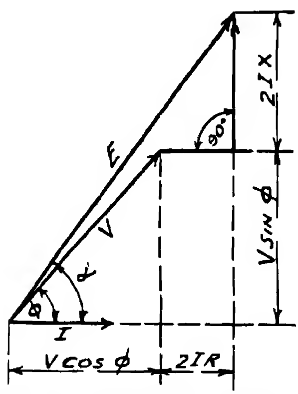


Fig. 293. Vector diagram of transmission line (Lagging Power Factor).
E—Voltage at sending end or power station end of line.
V—Voltage at receiving or load end.
R—Total resistance of single conductor, ohms.
X—Total reactance of single conductor, ohms.
I—Current flowing in each conductor, amps.
Less ϕ—Power factor of load current.
Cos α—Power factor of alternators.

$$\text{Percentage reguation} = \frac{E - V}{V} . 100$$

or alternatively $E - V$. 100

$$\text{Transmission efficiency} = \frac{V\cos\phi}{V\cos\phi + 2IR}$$

This method assumes a single-phase line transmitting half the amount of power. The percentage regulation on a three-phase line

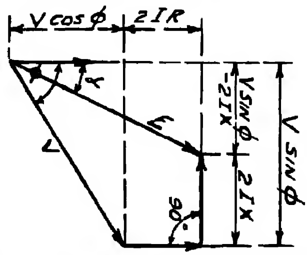


FIG. 294. Vector diagram of transmission line (Leading Power Factor).

is equal to that on a single-phase line transmitting half the amount of power. It will be observed that where electric power is transmitted over long distances, good regulation and high power factor are closely

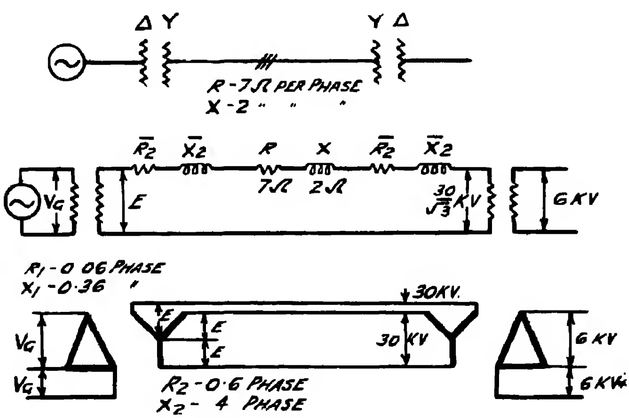


FIG. 295.

related. The problem of ensuring a steady voltage at the load end of a power line is simplified if a reasonably high power factor can be maintained. Another factor to be borne in mind is that where bulk supply is charged on a kVA demand basis, the question of power factor also arises. Examples illustrate the application of this formulae :

A sub-station receives 6,000 kVA at 6 kV, 0·8 power factor lagging

on the lower voltage side of a transformer from a power station, through a three-phase cable system having a resistance of 7 ohms and a reactance of 2 ohms per phase. Identical 6·6/33 kV transformers are installed at each end, the 6·6 kV windings being delta and the 33 kV star connected (Fig. 295). The resistance and reactance of the star-connected windings are 0·6 and 4 ohms, respectively, and for the delta winding 0·06 and 0·36 ohm.

Calculate the voltage at the power station busbars.

$$\text{Now } R2 = R2 + R1\left(\frac{E2}{E1}\right)^2$$

$$0{\cdot}6 + 00{\cdot}6\left(\frac{33}{\sqrt{3}}\Big/6{\cdot}6\right)^2 \textit{ using phase values.}$$

$$= 0{\cdot}6 + 0{\cdot}5$$

$$= 1{\cdot}1 \text{ ohm.}$$

$$\overline{X2} = X2 + X1\left(\frac{E2}{E1}\right)^2$$

$$= 4 + 0{\cdot}36\left(\frac{33}{\sqrt{3}}\Big/6{\cdot}6\right.$$

$$= 4 + 3 = 7 \text{ ohms.}$$

Total resistance of circuit $R = (2 \,.\, 1{\cdot}1) + 7 = 9{\cdot}2$ ohms.

„ reactance „ „ $X = (2 \,.\, 7) + 2 = 16$ ohms.

$$\text{Full load current } I_{FL} = \frac{6{,}000 \,.\, 1{,}000}{\sqrt{3} \,.\, 30{,}000} = 115 \text{ amps.}$$

$$\text{Ratio } \frac{E2}{E1} = \frac{33{,}000}{6{,}600} = 5$$

∴ with 6 kV on lower voltage side, higher voltage side = 30 kv.

$$\text{IR drop} = 9{\cdot}2 \,.\, 115 = 1{,}060 \text{ volts.}$$

$$\text{IX „} = 16 \,.\, 115 = 1{,}850 \text{ „}$$

$$\text{Phase voltage} = \frac{30{,}000}{\sqrt{3}} = 17{,}320.$$

From Fig. 293 it will be followed that

$$E = \sqrt{(V \text{ vos } \phi + 2IR)^2 + (V \sin \phi + 2IX)^2}$$

$$= \sqrt{(17{,}320 \,.\, 0{\cdot}8 + 1{,}060)^2 + (17{,}320 \,.\, 0{\cdot}6 + 1{,}850)^2}$$

$$= 19{,}300 \text{ volts.}$$

$$\text{Voltage at power station busbars } V_G = \sqrt{3} \,.\, E\left(\frac{E1}{E2}\right)$$

$$\therefore V_G = \sqrt{3} \,.\, 19{,}300 \,.\, \frac{6\cdot6}{33}$$

$$= 6{,}700 \text{ volts.}$$

Alternator p.f. $\cos\alpha = \dfrac{V\cos\phi + 2IR}{E}$

$$= \frac{17{,}320 \,.\, 0\cdot8 + 1{,}060}{19{,}300}$$

$$= 0\cdot78$$

Transmission efficiency $= \dfrac{V\cos\phi}{V\cos\phi + 2I\bar{R}}$

$$\frac{13{,}856}{14{,}916} = 93 \text{ per cent.}$$

The capacity current is generally neglected for comparatively short transmission lines operating at voltages below 100 kV, and, say, less than 40 miles long.

A 30-mile three-phase transmission line delivers 5,000 kW at 30 kV, 0·8 p.f. lagging. The resistance and reactance of single conductors are 0·72 and 0·6 ohms per mile, respectively. Consider as a single-phase system transmitting half the amount of power :

then $I = \dfrac{\text{Output}}{2V\cos\phi} = \dfrac{5{,}000}{2 \,.\, 30 \,.\, 0\cdot8} = 104$ amps.

$R = 0\cdot72 \,.\, 30 = 21\cdot6$ ohms resistance.

$X = 0\cdot6 \,.\, 30 = 18\cdot0$,, reactance.

$V\cos\phi = 30 \,.\, 0\cdot8 = 24$ kV. $\quad V\sin\phi = 30 \,.\, 0\cdot6 = 18$ kV.

$2I \,.\, R = 2 \,.\, 104 \,.\, 21\cdot6 = 4\cdot5$ kV. $\quad 2IX = 2 \,.\, 104 \,.\, 18 = 3.75$ kV.

28·5 kV. $\quad$ 21·75 kV.

$$\therefore E = 10^4\sqrt{(2\cdot85)^2 + (2\cdot175)^2}$$

$$= 10{,}000 \,.\, 3\cdot58$$

$$= 35{,}800 \text{ volts.}$$

Alternator p.f. $\cos\alpha = \dfrac{V\cos\phi + 2IR}{E}$

$$= \frac{28\cdot5}{35\cdot8} = 0\cdot8$$

Regulation $= \dfrac{35\cdot8 - 30}{30} \,.\, 100 = 19\cdot3$ per cent.

$$\text{Transmission efficiency} = \frac{24}{28\cdot5} \, . \, 100 = 84\cdot3 \text{ per cent.}$$

Calculate the reactance per phase from the following measurements taken on a three-phase line short-circuited at the receiving end. Line voltage 1,500 volts; Current per phase 50 amps.; Frequency 50 cycles per second.

$$\text{The line impedance } Z = \frac{E}{I}$$

Where E = line volts, and I = line current.

$$\therefore \text{ phase impedance} = \frac{1{,}500}{\sqrt{3} \, . \, 50} = 17\cdot3 \text{ ohms.}$$

$$\text{Impedance } Z = \sqrt{R^2 + X^2}$$

R = resistance per phase.

X = reactance per phase.

$$\begin{aligned} \therefore X &= \sqrt{Z^2 - R^2} \\ &= \sqrt{17\cdot3^2 - 12^2} \\ &= 12\cdot5 \text{ ohms per phase.} \end{aligned}$$

An overhead line consists of three wires $0\cdot8$ in. diameter, spaced 4 ft. apart. Calculate the resistance and reactance drops per mile of conductor for a line current of 400 amps. The specific resistance is $0\cdot67 \times 10^{-6}$ ohm per inch cube. Also estimate the line pressure at which corona would commence, taking $H_{max.}$ as 21 kV R.M.S. per cm. and frequency of 50 cycles per second.

$$\text{Resistance} \quad R = \frac{pl}{a}$$

$$= \frac{0\cdot67 \, . \, 10^{-6} \, . \, 5{,}280 \, . \, 12}{0\cdot7854 \, . \, 0\cdot8^2}$$

$$= 0\cdot0844 \text{ ohm per mile.}$$

$$\text{Reactance} \quad X = 2\pi f L$$

$$\text{now the inductance } L = 0\cdot741 \log_{10} \frac{s}{r} \text{ millihenries per mile;}$$

$$\begin{aligned} &= 0\cdot741 \, . \log_{10} . \frac{4\cdot12}{0\cdot4} \\ &= 0\cdot741 \log_{10} 120 \\ &= 0\cdot741 \, . \, 2\cdot0792 \\ &= 1\cdot54 \text{ millihenries per mile,} \\ &\quad \text{or } 1\cdot54 \, . \, 10^{-3} \text{ henry per mile.} \end{aligned}$$

$\therefore X = 2\pi \,.\, 50 \,.\, \dfrac{1 \cdot 54}{10^3} \qquad = 0 \cdot 484$ ohm per mile.

$\therefore$ IR drop per mile of conductor $= 400 \,.\, 0 \cdot 0844$
$= 33 \cdot 8$ volts

or $= \sqrt{3} \,.\, 33 \cdot 8 = 58 \cdot 6$ volts per mile of line.

IX drop per mile of conductor $= 400 \,.\, 0 \cdot 484$
$= 194$ volts

or, $= \sqrt{3} \,.\, 194 = 336$ volts per mile of line.

The voltage at which corona will commence is given by :

$$V_L = \sqrt{3} \,.\, H_{max.} \,.\, r \log_e \frac{S}{r}$$

$$= \sqrt{3} \,.\, 21 \,.\, 0 \cdot 4 \,.\, 2 \cdot 54 \,.\, \log_e \frac{4 \,.\, 12}{0 \cdot 4}$$

$$= \quad 3 \,.\, 21 \,.\, 0 \cdot 4 \,.\, 2 \cdot 54 \,.\, 2 \cdot 3 \log_{10} \frac{4 \,.\, 12}{0 \cdot 4}$$

$$= 177 \text{ kV R.M.S.}$$

Another problem associated with sub-station equipment is that of surges, and one form of surge which is responsible for many break-downs is the sudden transient high voltage wave set up as the result of a fault. A transmission line contains inductance and capacity, and energy is stored alternately in the two properties. In the event of a short-circuit, the energy in the line is suddenly required to dissipate itself, which it does in an oscillatory manner. The impressed voltage having been withdrawn, the current flowing at the time of the fault charges the line, which then discharges through the short circuit. The transient voltage, or surge, set up by some such change in the stored energy travels along the line and will ultimately reach the sub-station or terminal point, where it may be dangerous. The effect may be greatly minimised at the remote end by making use of the reflection which occurs when the characteristics of the line change abruptly. At such a point, secondary waves are set up, which are propagated along the line in both directions, and the voltage transmitted into the new section is the sum of the original voltage and the reflected wave. If the surge impedance of the new section is greater than that of the original line, a voltage rise occurs, the transmitted voltage lying between its original value and twice that amount. Should the surge impedance of the new section be less than that of the original section, the voltage will be reduced and a current rise occurs. The surge

impedance of a low resistance line is measured by $Z = \sqrt{\frac{L}{C}}$, and since cables exhibit a much smaller ratio of L/C than overhead lines, it follows that the inclusion of a short length of cable between the end of the line and the transformer may afford a certain degree of protection against such surges. The cable has the effect of reducing the voltage developed in the sub-station by a surge originating in the overhead line. The magnitude of the rise or fall in voltage can be estimated, and the surge voltage is given by $E = I\sqrt{\frac{L}{C}}$. In an insulated cable, the ratio $\frac{L}{C}$ is less than in an overhead line, so that the surge obtaining at the sub-station plant is reduced by the insertion of cable. The cable should have a dielectric of high permitivity to give a low $\frac{C}{L}$ ratio. Vulcanised bitumen or V.I.R. are better in this respect, but are not suitable from other viewpoints. Assume the impedance of the new section to be greater than that of the original impedance, then the transmitted voltage wave lies between the original value E and 2E, *i.e.*, a voltage rise at the junction (Fig. 296 (*a*)).

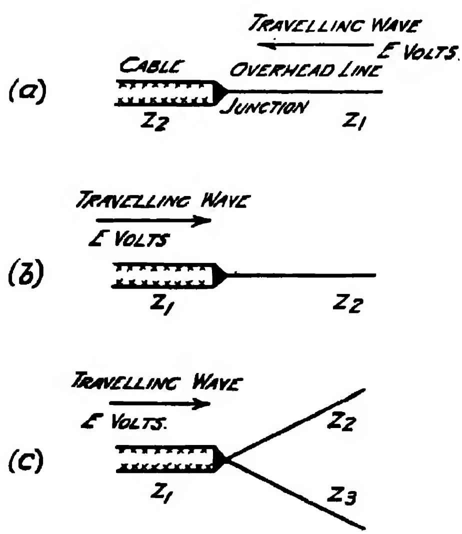


Fig. 296.

Let Z1 = impedance of original section.
„ Z2 = „ „ new section.

For cable $Z2 = \sqrt{\frac{L2}{C2}}$

overhead line $Z1 = \sqrt{\frac{L1}{C1}}$

The surge voltage and current can be connected by the equation $E = I\ Z1$.

Let I1 = reflected current (opposite sign to I)
„ E1 = „ voltage (same sign as E)
or, = I1 Z1.

$$\text{Now, } \frac{\text{transmitted voltage}}{\text{transmitted current}} = \frac{E + E1}{I - I1} = Z2$$

$$\text{transmitted current} = I - I1$$

$$\text{„ voltage} = (I - I1) \,.\, Z2.$$

Consider the impedance of the new section to be less than that of the original impedance, in which case there is a decrease in voltage at the junction (Fig. 296 (*b*)).

For cable $Z1 = \sqrt{\frac{L1}{C1}}$

overhead line $Z2 = \sqrt{\frac{L2}{C2}}$

Let I1 = reflected current (same sign as I)
„ E1 = „ voltage (opposite sign to E)

$$\frac{\text{transmitted voltage}}{\text{transmitted current}} = \frac{E - E1}{I + I1} = Z2$$

$$\text{transmitted current} = I + I1$$

$$\text{„ voltage} = (I + I1)\ Z2.$$

Now consider the case of a surge wave meeting two paths into which it may flow (Fig. 296 (*c*)) :

$$\text{Let the total impedance of lines} = Z_T = \frac{1}{Z2} + \frac{1}{Z3}$$

$$I = .\ \frac{E}{Z_T}$$

If Z_T be less than Z_1 there will be a decrease in voltage

I_1 = reflected current (same sign as I)

E_1 = „ voltage (opposite sign to E)

or, $I_1 Z_1$

then $Z_T = \dfrac{E - E1}{I + I_1}$

transmitted current = $(I + I_1)$

„ voltage = $(I + I_1) Z_T$.

The currents travelling in each branch (Z2 and Z3) will be proportional to their respective impedances :

$$\therefore \text{ current in } Z2 = (I + I_1)\frac{Z_T}{Z2}$$

$$\text{„ „ } Z3 = (I + I_1)\frac{Z_T}{Z3}$$

A cable has an inductance of 0·3 millihenries per mile, and a capacity of 0·4 microfarads per mile, the line terminates in an overhead line having an inductance of 1·5 millihenries per mile, and capacity 0·012 microfarads per mile. Estimate the instantaneous voltage at the junction of the cable and the overhead line due to a surge voltage of 10 kV :

(1) travelling along the cable to the junction ;

(2) „ „ „ overhead line „

Equating the two forms of energy we have

$$\tfrac{1}{2} CE^2 = \tfrac{1}{2} LI^2 \text{ joules}$$

$$\text{from which } E = I\sqrt{\frac{L}{C}}$$

Where C = capacity of circuit in farads.

„ L = inductance of circuit in henries.

(1) $$Z1 = \sqrt{\frac{L1}{C1}} = \sqrt{\frac{300 \,.\, 10^{-6}}{0{\cdot}4 \,.\, 10^{-6}}} = 27 \text{ ohms.}$$

$$Z2 = \sqrt{\frac{L2}{C2}} = \sqrt{\frac{1{\cdot}500 \,.\, 10^{-6}}{0{\cdot}012 \,.\, 10^{-6}}} = 353 \text{ ohms.}$$

Since Z2 is greater than Z1, there will be a voltage rise at the junction.

$$E = 10{,}000 \text{ volts, } I = \frac{E}{Z1} = \frac{10{,}000}{27} = 380 \text{ amps.}$$

$$Z2 = \frac{E + E1}{I - I_1} = \frac{10{,}000 + E1}{380 - I_1} = 353$$

$$E1 = I1 \qquad Z_1 = I_1 \,.\, 27$$

$$\therefore \frac{10{,}000 + 27\, I_1}{380 - I_1} = 353, \text{ from which } I_1 = 326 \text{ amps.}$$

$$\begin{aligned} \text{Transmitted current} &= 380 - 326 \\ &= 54 \text{ amps.} \\ \text{,,} \qquad \text{voltage} &= 54 \,.\, 353 \\ &= 19{,}000 \text{ volts (Fig. 297 } (a)). \end{aligned}$$

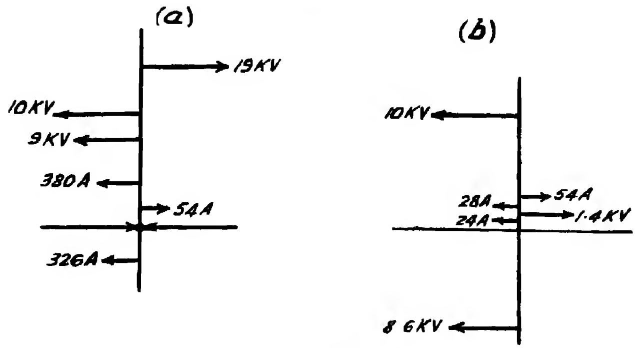


FIG. 297.

(2) $$Z_1 = \frac{E - E1}{I + I_1} = \frac{10{,}000 - E1}{28 + I_1} = 27$$

$$I = \frac{10{,}000}{353} = 28 \text{ amps.} \qquad E1 = I_1\, Z_1$$

$$= I_1 \,.\, 353$$

$$\therefore \frac{10{,}000 - 353\, I_1}{28 + I_1} = 27$$

$$\begin{aligned} \text{from which } I_1 &= 24 \text{ amps.} \\ \text{Transmitted current} &= 28 + 24 = 52 \text{ amps.} \\ \text{,,} \qquad \text{voltage} &= 27 \,.\, 52 = 1{,}400 \text{ volts (Fig. 297 } (b)). \end{aligned}$$

A surge voltage of 20 kV travelling in a transmission line of 500 ohms, meets a junction point where two lines of impedances, 700 and 200 ohms, join. Estimate the voltage and the current for the surge transmitted into each of the two circuits (Fig. 298).

$$\text{Now } Z_T = \frac{1}{Z2} + \frac{1}{Z3} = \frac{1}{700} + \frac{1}{500} = 155 \text{ ohms.}$$

Z_T is less than Z1, therefore there will be a decrease in pressure at the junction point.

$$E = 20 \text{ kV}, \qquad I = \frac{20{,}000}{500} = 40 \text{ amps.}$$

$$Z_T = \frac{E - E1}{I + I_1} \qquad \text{Now, } E1 = I_1 Z_1$$

$$= I_1 \,.\, 500$$

$$= \frac{20{,}000 - 500\, I_1}{40 + I_1} = 155$$

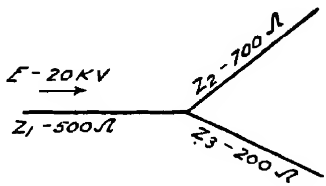


FIG. 298.

from which $I_1 = 21$ amps.

Transmitted current $= (I + I_1)$

$= 40 + 21 = 61$ amps.

„ voltage $= (I + I_1)\, Z_T$

$= 61 \,.\, 155$

$= 9{,}450$ volts.

The currents travelling in each branch (Z2 and Z3) are proportional to their respective impedances.

$$\text{Therefore current in Z2} = (I + I_1)\frac{Z_T}{Z2}$$

$$= 61 \,.\, \frac{155}{70}$$

$$= 14 \text{ amps.}$$

$$\text{current in Z3} = (I + I_1)\frac{Z_T}{Z3}$$

$$= 61 \,.\, \frac{155}{200}$$

$$= 47 \text{ amps.}$$

A 45 kV, three-phase, 50-cycle overhead line, 40 miles long, with pin insulators, has three conductors spaced 45 in. apart, the conductor diameter is 0·4 in. Estimate (1) charging current per line ; (2) total charging kVA ; (3) reactance volts per line when carrying 120 amps.

Capacity C $= \dfrac{0 \cdot 0388\ K}{\log_{10} \dfrac{S}{r}}$ K for air = 1

Three-phase line with conductors arranged at corners of an equilateral triangle. $\Big\} = \dfrac{0 \cdot 0388}{\log_{10} \dfrac{45}{0 \cdot 2}} \quad \dfrac{0 \cdot 0388}{2.352}$

$= 0 \cdot 0165$ microfarads per mile.

Total capacity of line $= 0 \cdot 0165 \,.\, 40$
$= 0 \cdot 66$ mfds.

Charging current per line I_c $= 2\pi f \,.\, C \,.\, \dfrac{E_L}{\sqrt{3}}$

$= 2\pi \,.\, 50 \,.\, \dfrac{0 \cdot 66}{10^6} \cdot \dfrac{45{,}000}{\sqrt{3}}$

$= 5 \cdot 39$ amps.

Total charging kVA $= \dfrac{\sqrt{3} \,.\, E_L \,.\, I_c}{10^3}$

$= \sqrt{3} \,.\, 45 \,.\, 5 \cdot 39$

$= 420$ kVA.

Reactance volts per line $= \sqrt{3} \,.\, I \,.\, X. \qquad X \quad 2\pi f.L.$

$= \sqrt{3} \,.\, 120 \,.\, 2\pi. \quad L = \; 0 \cdot 741 \log_{10} \dfrac{45}{0 \cdot 2}$

$= 1 \cdot 742\ mH$ per in. of conductor.

$= \sqrt{3} \,.\, 120 \,.\, 2\pi \,.\, 50 \,.\, 1 \cdot 742 \,.\, 40.$

$= 4{,}550$ volts.

With unsymmetrical spacing of conductors, $S = \sqrt[3]{S1 \,.\, S2 \,.\, S3}$.

High voltage insulators function as electrical condensers when they are subjected to an alternating potential, the metalwork forming the plates, and the insulating material the dielectric. The capacity effect assumes greater importance when a number of units are con-

nected to form a string. One is a series capacity between units, and the other an earth capacity from each unit. The end units carry the cumulative charges of the others, which results in a greater voltage drop across them. There is a limit to which the number of these units can be assembled, but by including guard or shielding rings the number can be increased. The latter secure a more uniform stress distribution along an assembled string of insulators.

A suspension type insulator consists of two suspended porcelain discs with metal links. The capacity of each of the links to earth is 5 per cent. of the capacity between the links. If the voltage of the live wire to earth is 10 kV, calculate the voltage across each of the discs :

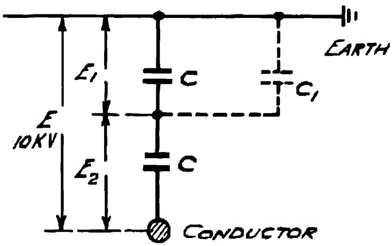


FIG. 299.

Let C = capacity between the links.
C_1 = ,, of each link to earth.
C_1 = 5 per cent. C. If $C_1 = 5$
C = 100.

From Fig. 299 . . . . (1)

$$E_1 (C + C_1) = E_2 . C.$$
$$E = E1 + E2$$
$$\therefore \quad E_1 = 10 - E_2$$
$$\text{or} \quad E_2 = 10 - E_1$$

From (1)

$$(10 - E2)(100 + 5) = E2 . 100$$
$$E2 = \frac{1050}{205} = 5{\cdot}1 \text{ kV.}$$
$$\therefore \quad E1 = 10 - 5{\cdot}1 = 4{\cdot}9 \text{ kV.}$$

Alternatively,

Let E2 be the voltage of the intermediate section of connecting metalwork, so that the drop across the first insulator (from line) is (E − E1) and across the second, E1 :

Let 100C be the capacities of the porcelain insulators, and 5C the capacity to earth of the metal link.

The charging current through the first condenser is :

$$I1 = (E - E1) \,.\, 2\pi f.C.$$
$$= (E - E1) \,.\, \omega \,.\, 100C.$$

through the second condenser :

$$I2 = E1 \,.\, 2\pi f.C.$$
$$= E \,.\, \omega \,.\, 100C.$$

The difference between these two currents is the charging current which flows through the capacity 5C to earth, *i.e.*,

$$I1 - I2 = E1 \,.\, 5C \,.\, \omega.$$

also $$I1 - 12 = (10 - 2E1) \,.\, 100C \,.\, \omega.$$

$$\therefore \quad E1 \,.\, 5C \,.\, \omega = (10 - 2E1) \,.\, 100C \,.\, \omega$$

$$E1 = \frac{(10 - 2E1) \,.\, 100}{5}$$
$$= (10 - 2E1) \,.\, 20$$
$$E1 = 200 - 40E_1$$
$$41E1 = 200 \therefore E1 = 4{\cdot}9 \text{ kV},$$

and $E2 = 5{\cdot}1$ kV as before.

The calculation of the voltages across the individual units of a string consisting of several discs is much more complex even although the series and earth capacitances of each unit are assumed to be uniform. Fig. 300 shows the system of capacities for a four-unit string. Starting at the earthed side, the voltages and currents are successively E_1, E_2 - - - - and I_1, I_2 - - - as shown. C is the series capacitance of each unit and k its capacitance to earth. The total capacitance to earth at link 1 is C and k in parallel, *i.e.*,

$$C_1 = C + k$$

At link 2 the capacitance to earth is k in parallel with C and C_1 in series, *i.e.*,

$$C_2 = k + CC_1/(C + C_1)$$
$$= (C^2 + 3Ck + k^2)\,(2C + k)$$

Similarly,

$$C_3 = k + CC_2/(C + C_2)$$
$$= \frac{C^3 + 6C^2k + 5Ck^2 + k^3}{3C^2 + 4Ck + k^2}$$

The capacitance C_n at each successive point for a string made of a

large number of units can be found from the series parallel systems of k in parallel with C and C_{n-1} in series. Thus,

$$C_4 = \frac{C^4 + 10C^3k + 15C^2k^2 + 7Ck^3 + k^4}{4C^3 + 10C^2k + 6Ck^2 + k^3}$$

and

$$C_5 = \frac{C^5 + 15C^4k + 35C^2k^3 + 28C^3k^2 + 9Ck^4 + k^5}{5C^4 + 20C^3k + 21C^2k^2 + 8Ck^3 + k^4}$$

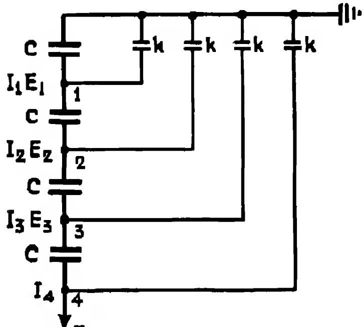


FIG. 300.

Each of the numerical coefficients in the foregoing capacitances is a coefficient in a binomial expansion which can be written N^r_n and which is the coefficient of the rth term in an expansion of the nth power, *e.g.*, $N^3_4 = 6$. If also k is written m C, the general expression derived by induction for the total capacitance to earth at any link is, $C_n = CX$

$$\left\{ \frac{1 + N^n_n + {}_1m + N^{n-1}_{n+2}\, m^2 + N^{n-2}_{n+3}\, m^3 + \text{----}\, m^n}{n + N^{n-1}_{n+1}\, m + N^{n-2}_{n+2}\, m^2 + \text{----}\, m^{-1}} \right\} \quad \ldots\ldots \quad (1)$$

In Fig. 300 the current at any point, say, 4 is $I_4 = I_3 + E_4\omega\, k$ since the currents flows into the capacitance C between points 3 and 4 as flows out of it. As $I_4 = \omega E_4C_4$ and $I_3 = \omega E_3C_3$,

$$\omega E_4C_4 = \omega E_3C_3 + E_4\omega k, \textit{ i.e.}, E_3 = E_4\,(C_n - k)/C3$$

$$\text{or more generally, } E_{n-1} = E_n\,(C_n - k)/C_{n-1} \quad . \quad . \quad . \quad (2)$$

$$\text{But } C_n = k + C\,C_{n-1}/(C + C_{n-1}) \text{ so that (2) becomes}$$

$$E_{n-1} = C/(C + C_{n-1}) \quad . \quad . \quad . \quad (3)$$

When the general expression for C_{n-1} as at equation (1) is used in equation (3), C cancels out and putting the expression within the brackets at (1) as $f(N._m)$ we get $E_{n-1} = E_n/[1 + f(N._m)] \ldots$ (4). Although equation (1) looks formidable for calculating, in practice it is not so much because k is only a few per cent. of C making m small enough for the powers higher than the square to be ignored without introducing serious errors. The values of $f(N._m)$ for successive values of n (according to the number of units making up a string), can be

calculated with the aid of a table of binomial coefficients, whence the voltages at the successive points n, n–1 . . . 2, 1 are found. In Table 23, the values of $f(N._m)$ and E_n have been calculated from equations (1) and (4) respectively for an eleven-unit string of discs, k being taken as 4 per cent. The fourth column shows how the units nearest to the line conductor are much more highly stressed than those adjacent to the earthed anchorage.

TABLE 23.

Unit	$f(N._m)$	$E_n / [1+f(N._m)]$	Voltage across unit (E_n—E_{n-1})
11			0·182 E
	0·223	0·818 E	
10			0·152 E
	0·229	0·666 E	
9			0·125 E
	0·232	0·541 E	
8			0·107 E
	0·347	0·434 E	
7			0·089 E
	0·260	0·345 E	
6			0·076 E
	0·284	0·269 E	
5			0·066 E
	0·323	0·203 E	
4			0·058 E
	0·400	0·145 E	
3			0·051 E
	0·584	0·0935 E	
2			0·048 E
	1·040	0·0458 E	
1			0·046 E

Units are numbered from the earthed end of the earthed end of the string. $E = E_{n\ (max.)}$ = line-to-earth voltage of conductor.

A suspension type insulator consists of four similar units and the voltage between the line conductor and earth is 60 kV. The ratio of capacity of each unit insulator to the capacity, relative to earth, of

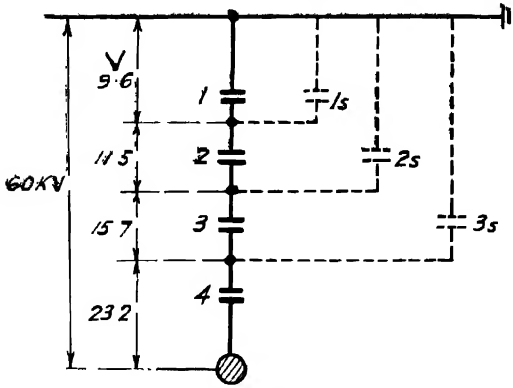


FIG. 301.

each intermediate section of the connecting metalwork is five to one, assuming no leakage takes place. Estimate the voltage across each unit.

Adopting the tabular method, Table 24, of working, and assuming main capacity to be 1C ; shunt capacity 0·2C ; volts across insulator 1 as V, and designate as in Fig. 301.

TABLE 24

Across	Current	Voltage	Value (kV)
1	ωCV	* V	9·6
1S	0·2 ωCV	V	
	1·2 ωCV	1·2 V	11·5
2S	0·44 ωCV	2·2 V	
3	1·64 ωCV	* 1·64 V	15·7
3S	0·768ω	3·84 V	
4	2·408	* 2·408 V	23·2
	* Total .	6·248 V	60

The first two lines are straightforward, then against 2, add the previous currents and divide by ωC to get the volts for 2S. This in turn multiplied by $0 \cdot 2 \omega C$ gives the current for 2S. This, added to the above, gives the current for 3, and so on. Adding the volts across the insulators as shown in table, and equating to 60 kV, gives the voltage V across top insulator.

Underground cable systems require a large charging current—approaching 1 ampere per mile of 11 kV cable—which may necessitate some 5,000 to 10,000 kVA or more being required to charge a system. On the other hand, capacity current improves the overall power factor and the regulation of the system.

A single-phase concentric cable, 15 miles long, when connected to 10 kV, 50-cycle busbars, takes a charging current of 5 amps. Estimate the capacity per mile of cable.

Charging current $I_C = \omega CE$ amps.

$$5 = 2\pi \, . \, 50 \, . \, C \, . \, 10{,}000$$

$$\therefore \qquad C = \frac{5}{2\pi \, . \, 50 \, . \, 10{,}000} \text{ farads}$$

$$= \frac{5 \, . \, 10^6}{2\pi \, . \, 50 \, . \, 10{,}000} \text{ microfarads}$$

$$= 1 \cdot 6 \text{ mfds.}$$

$$\therefore \text{ Capacity per mile of cable} = \frac{1 \cdot 6}{15} = 0 \cdot 106 \text{ mfds.}$$

Show diagrammatically the distribution of electrostatic capacity in a three-core, three-phase, lead-sheathed cable.

The capacity of such a cable measured between any two of the conductors, the sheathing being earthed, is $0 \cdot 3$ microfarads per mile. Find the equivalent star-connected capacity and the kVA required to keep 10 miles of the cable charged when connected to 20 kV, 50-cycle, busbars.

Fig. 302 (*a*) shows diagrammatically the distribution of electrostatic capacity in a three-core cable of the class mentioned. The

capacities between the three conductors (X, Y, Z) are represented by condensers CA, whilst the capacity between each conductor and the lead sheath S is represented by condensers CB. Fig. 302 (*b*) shows a simplified diagram of the arrangement, from which it will be noted

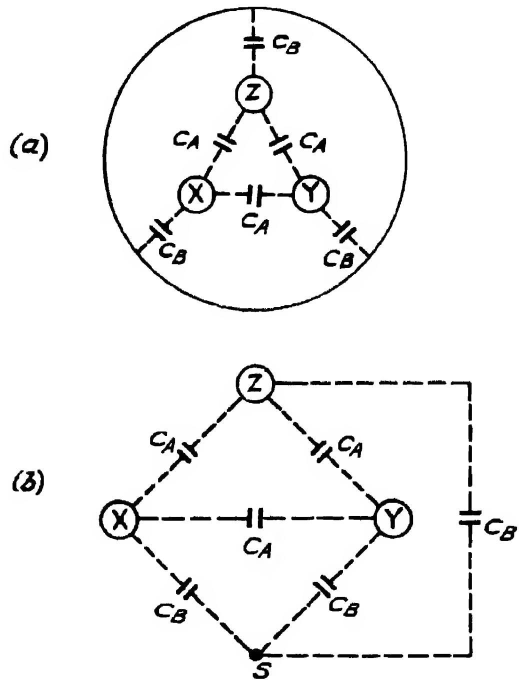


FIG. 302.

that there are three parallel circuits between conductors X and Y, namely :

A direct circuit of capacity CA (X to Y).
A circuit of capacity $\frac{1}{2}$CA (X Z Y).
" " " " $\frac{1}{2}$CB (X S Y).

$\therefore$ Total capacity between X and Y = 3/2 CA + $\frac{1}{2}$CB.

The condensers CA are mesh connected and the condensers CB are star-connected, the lead sheath forming the star point.

Current taken by CA = $\sqrt{3} \cdot \omega \cdot CA \cdot E_L$.

Let C be the star-connected capacity to take the same line current, the applied voltage then being $E_L/\sqrt{3}$. For these to be equal

$$\frac{\omega . C . E_L}{\sqrt{3}} = \sqrt{3} . \omega . CA . E_L$$
$$C = 3\ CA.$$

The equivalent star-connected capacity of the system shown in Fig. 302 (*a*) (*i.e.*, CA and CB), would be given by

$$CA + CB = 3CA + CB = 2(3/2\ CA + \tfrac{1}{2}CB).$$

= twice the capacity measured between any two conductors.

Substituting the data given in example :

Equivalent star-connected capacity = 2 . 0·3
0·6 mfds. per mile

Charging current per mile of cable, $I_c = \omega . C . \frac{EL}{\sqrt{3}}$

$$= 2\pi . 50 . \frac{0{\cdot}6}{10^6} . \frac{20{,}000}{\sqrt{3}}$$

$= 2{\cdot}2$ amps.

Charging kVA per mile $= \dfrac{\sqrt{3} . E_L . I_c}{10^3}$

Total charging kVA $= \dfrac{\sqrt{3} . E_L . I_c . L}{10^3}$

$$= \frac{\sqrt{3} . 20{,}000 . 2{\cdot}2 . 10}{10^3}$$

$= 755$ kVA.

A single-core high-voltage cable has a conductor diameter of 0·15 in., the diameter of the cable over the insulation being 1 in. ; calculate the insulation resistance per mile of cable, given that the insulating material has a specific resistance of $5{\cdot}10^{10}$ ohms per cm.³

R = external radius of insulation.
r = internal „ „ „
pi = specific resistance of insulation, ohms per cm.³
L = length of cable, cm.

$$\text{Total insulation resistance, } R_T = \frac{2\cdot 3\, pi}{2\pi L} \,.\, \log_{10} \frac{R}{r} \text{ ohms.}$$

$$= \frac{2\cdot 3 \,.\, 5 \,.\, 10^{10}}{2\pi \,.\, 1 \,.\, 5280 \,.\, 12 \,.\, 2\cdot 54} \,.\, \log_{10} \frac{0\cdot 5}{0\cdot 075}$$

$$= 94{,}000 \text{ ohms per mile.}$$

On a condenser installed in a sub-station to improve the power factor on the high voltage side it was found that the R.M.S. current in the condenser exceeded the value given by dividing the R.M.S. voltage by the capacity reactance. The reason for the R.M.S. current in the condenser exceeding the quotient of the R.M.S. voltage and capacity reactance is the presence of harmonics in the voltage wave. Thus, suppose the voltage wave to be represented by

$$E = E_1 \operatorname{Sin} \phi + E_n \operatorname{Sin} n\phi$$

where E_1 is the amplitude of the fundamental, and E_n is that of the nth harmonic.

Let C be the capacity of the condenser in farads and f the frequency of supply. Then the amplitude of the fundamental current taken by the condenser $= I_1 = 2\pi f C E_1$; and that of the nth harmonic current $I_n = 2\pi n f C E_n$.

$$\therefore \text{ R.M.S. value of current} = 0\cdot 707 \sqrt{I_1^2 + I_n^2}$$

$$= 0\cdot 707 \,.\, 2\pi f C \,.\, \sqrt{E_1^2 + (nE_n)^2} \quad . \quad . \quad . \quad . \quad (1)$$

But R.M.S. value of voltage $= 0\cdot 707 \sqrt{E_1^2 + E_n^2}$, so that the R.M.S. value of the voltage divided by the capacity reactance for the fundamental (namely, the reactance which is usually calculated).

$$= 0\cdot 707 \sqrt{E_1^2 + E_n^2} \div \frac{1}{2\pi f C}$$

$$= 0\cdot 707 \,.\, 2\pi f C \sqrt{E_1^2 + E_n^2} \quad . \quad . \quad . \quad . \quad (2)$$

Comparison of expressions (1) and (2) shows that owing to the presence of n in (1), the R.M.S. value of the current is greater than the quotient of the R.M.S. voltage and the capacity reactance for the fundamental. Since the current through the condenser is dependent only upon the voltage wave and upon the capacity, a load on the high voltage network can have no influence upon the condenser current so long as the wave-form of the voltage remains unaltered. Further information on the influence of voltage harmonics upon power-factor correction by condensers and the effect of the harmonics upon the method of charging

for electrical energy will be found in a paper read by E. Hughes before the British Association and published in *Engineering*, 13th August, 1936.

Condenser action, or capacity, affects switchgear, cables, and other higher voltage electrical equipment, and the effect of varying the degree of insulation, and the materials used, will be noted from this example :

Two plates 8 mm. apart are charged to 12 kV ; estimate :

(1) stress with an air dielectric.

(2) „ „ a compound dielectric (50 per cent. mica, $k = 5$; and 50 per cent. air, $k = 1$).

(3) „ „ 90 per cent. mica, and 10 per cent. air.

(1) Stress $= \dfrac{12}{0 \cdot 8} =$ 15 kV per cm.

(2) Equivalent air $= \dfrac{0 \cdot 4}{1} + \dfrac{0 \cdot 4}{5}$

$= 0 \cdot 48$ cm.

Air stress $= \dfrac{12}{0.48} = 25$ kV per cm.

Mica stress $= \dfrac{\text{Air Stress}}{\text{Permitivity}} = \dfrac{25}{5} = 5$ kV per cm.

Air volts $= 25 \,.\, 0 \cdot 4 = 10$ kV

Mica volts $= 5 \,.\, 0 \cdot 4 = 2$ „

12 „ total.

(3) Equivalent air = (10 per cent. 4 mm.) + (90 per cent. 4 mm.)

$= \dfrac{0 \cdot 04}{1} + \dfrac{0 \cdot 36}{5}$

$= 0 \cdot 112$ cm.

Air stress $= \dfrac{12}{0 \cdot 112} = 107$ kV per cm.

Mica stress $= \dfrac{107}{5} = 21 \cdot 4$ kV per cm.

Air volts $= 107 \,.\, 0 \cdot 04 = 4 \cdot 3$ kV

Mica volts $= 21 \cdot 4 \,.\, 0 \cdot 36 = 7 \cdot 7$ „

12·0 „ total.

A condenser bushing consists essentially of a number of concentric cylinders usually in the form of a metal foil, separated by some suitable insulating material such as treated paper or the like. The whole is wound on the main current carrying conductor which may either take the form of solid rod or tube. These foils are essentially the make-up of a bank of condensers in series and can be so designed that the resulting voltages from these capacities give a constant maximum stress. The general notation for the stress distribution in high voltage cables is applicable here.

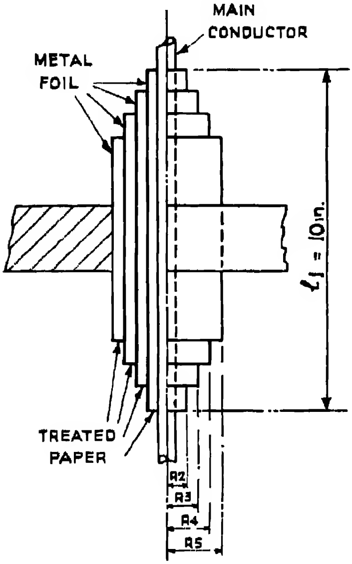


FIG. 303.

A conductor of 0·5 in. diameter with a bushing of five layers, each 0·1 in. thick, has a total potential difference of 30 kV applied. If the innermost foil is 10 in. long what will be the lengths of the remaining foils for equal maximum stress?

$$\text{Now } E = H_{max.}\, r \log_e R/r$$

denoting radii from R_1 to R_6 (Fig. 303), R_1 being X the conductor radius.

$$E = H_{max.} (R_1 \log_e R_2/R_1 + R_2 \log_e R_3/R_2 + \ldots R_5 \log_e R_6/R_5)$$

$$30 = H_{max.} \,.\, 2{\cdot}3 \left(0{\cdot}25 \log \frac{0{\cdot}35}{0{\cdot}25} + 0{\cdot}35 \log_{10} \frac{0{\cdot}45}{0{\cdot}35} + 0{\cdot}45 \log_{10} \frac{0{\cdot}55}{0{\cdot}45} + 0{\cdot}55 \log_{10} \frac{0{\cdot}65}{0{\cdot}55} + 0{\cdot}65 \log_{10} \frac{0{\cdot}75}{0{\cdot}65}\right)$$

$$30 = H_{max.}\, 2{\cdot}3 \,.\, 0{\cdot}2$$

$\therefore H_{max.} = 67$ kV per in. approx.

Then

$$E_1 = H_{max.} R_1 \log_e R_2/R_1$$

$$= 67 \,.\, 0{\cdot}25 \,.\, 2{\cdot}3 \log_{10} \frac{0{\cdot}35}{0{\cdot}25}$$

$$= 5{\cdot}7 \text{ kV approx.}$$

Similarly $E_2 = 5 \cdot 9$ kV ; $E_3 = 6 \cdot 05$ kV ; $E_4 = 6 \cdot 15$ kV ; $E_5 = 6 \cdot 2$ kV. Now the capacity of a tubular condenser is given by

$$C = \frac{C_1 \cdot k}{10^6 \cdot \log_{10} R_2/R_1}$$

microfarads per cm. where C_1 is a constant and k is the specific inductive capacity, or can be written $C = \dfrac{\text{constant}}{\log_{10} R_2/R_1}$ mfds. per cm.

$$= \frac{\text{constant} \cdot l_1}{\log_{10} R_2/R_1} \text{ where } l_1 = \text{length} = 10 \text{ in.}$$

$$\therefore C_1 = \frac{\text{constant} \cdot 10}{\log_{10} \dfrac{0 \cdot 35}{0 \cdot 25}} = \frac{\text{constant} \cdot 10}{0 \cdot 1461}$$

Now the charges are equal, *i.e.*, $Q_1 = Q_2 = Q_3$, etc.

$$\therefore C_1 E_1 = C_2 E_2 = C_3 E_3, \text{ etc.}$$

$$\therefore \frac{C_1}{C_2} = \frac{E_2}{E_1} \text{ and } \frac{C_2}{C_3} = \frac{E_3}{E_2}, \text{ etc.}$$

$$\frac{C_1}{C_2} = \frac{E_2}{E_1} = \frac{5 \cdot 9}{5 \cdot 7} = 1 \cdot 03.$$

Now constant $\times$ 10

$$\frac{\dfrac{\text{constant} \times 10}{0 \cdot 1461}}{\dfrac{\text{constant} \times l_2}{\log_{10} \dfrac{R_3}{R_2}}} = \frac{C_1}{C_2} = \frac{\dfrac{10}{0 \cdot 1461} \cdot \log_{10} \dfrac{R_3}{R_2}}{l_2}$$

$$\therefore l_2 = \frac{68 \cdot 5 \cdot \log_{10} \dfrac{0 \cdot 45}{0 \cdot 35}}{1 \cdot 03} = 7 \cdot 14 \text{ in.}$$

l_3, l_4 and l_5 can be calculated in a similar manner. An alternative method of approach is as follows :

$$Q_1 = Q_2 = Q_3, \text{ etc.}$$
$$C_1 E_1 = C_2 E_2 = C_3 E_3, \text{ etc.}$$

$$\frac{\text{constant}\,.\,l_1}{\log_e R_2/R_1}\,.\,H_{max}.\,R_1 \log_e R_2/R_1 = \frac{\text{constant}\,.\,l_2}{\log_e R_3/R_2}\,.\,H_{max}\,.\,R_2 \log_e \frac{R_3}{R_2}, \text{ etc.}$$

$$\therefore l_1 R_1 = l_2 R_2 = l_3 R_3, \text{ etc.}$$

if $l_1 = 10$ in. then $l_2 = 7\cdot14$ in., $l_3 = 5\cdot55$ in., $l_4 = 4\cdot55$ in. and $l_5 = 3\cdot85$ in. This is a much simpler calculation and does not involve the possibility of errors.

An equivalent A.C. network is represented by an impedance with an inductance of 0 1 henry and a resistance of 25 ohms shunted by a capacity of 70 microfarads. Calculate the frequency at which this combination acts like a non-inductive resistance. The circuit is shown in Fig. 304 (*a*), and the vectors for the voltage and currents are represented in (*b*). Let f be the required frequency and E be the supply voltage, then current through $C = I_c = 2\pi f CE$. and the current through $L = I_L$.

$$= \frac{E}{\sqrt{R^2 + (2\pi f L)^2}}$$

Let ϕ be the angle of lag of I0 behind E. In order that this combination may act as a non-inductive resistance, the resultant current I

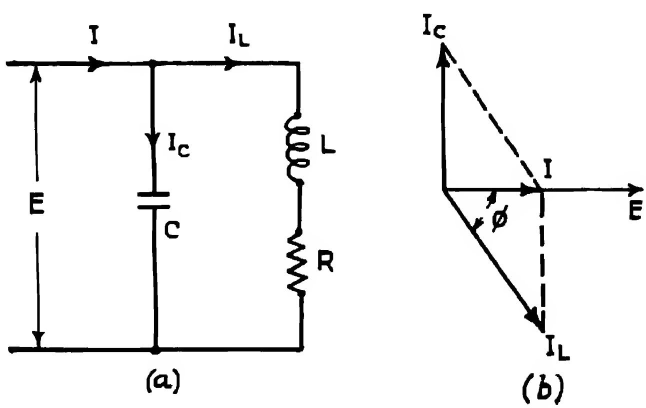


FIG. 304.

must be in phase with E, and the capacity current must equal the watt-less component of I_L, *i.e.*, $I_C = I_L \text{ Sin } \phi$

$$\therefore 2\pi f CE = \frac{E \,.\, 2\pi f L}{R^2 + (2\pi f L)^2}$$

$$\therefore R^2 + (2\pi f L)^2 = \frac{L}{C} \quad . \quad . \quad . \quad . \quad (1)$$

substituting the values given we have :

$$25^2 + (2\pi f \,.\, 0\cdot 1)^2 = \frac{0\cdot 1 \,.\, 10^6}{70}$$

$$\therefore f = 45\cdot 2 \text{ cycles per sec.}$$

Also, $I = I_L \text{ leos } \phi$

$$= \frac{E \,.\, R \,.}{R^2 + (20 f L)^2} = \frac{E \,.\, R \,.\, C \,.}{L}$$

The last step follows from expression (1)

$\therefore$ non-inductive resistance equivalent to this circuit

$$= \frac{E}{I} = \frac{L}{RC}$$

$$= \frac{0\cdot 1 \,.\, 10^6}{25\cdot 70} \; 57\cdot 2 \text{ ohms.}$$

Power Factor Improvement. The installation of power factor, or phase advancing plant, in industrial and mining sub-stations is quite frequent, and some problems relating to this equipment are of importance.

In order to decide whether the installation of power factor improving plant is justified economically, it is necessary to know what savings would accrue by its adoption. This plant may be adopted for two reasons : (1) to enable existing distribution networks to carry additional load ; and (2) to reduce the existing kVA demand.

If a consumer pays for a supply on a two-part tariff, *i.e.*, £*x* per kVA of maximum demand, plus a unit charge, then it is in his own interest to reduce the kVA demand. Before an estimate can be given, it is necessary to know the cost per annum per kVA of maximum demand, and the capital cost per kVA of power factor improving plant, together with the interest and depreciation rate thereon. The nett annual saving is then the difference between the reduction in annual

electricity charges and the annual loss of interest and depreciation. It is rarely justifiable to raise the power factor to unity, and there is a particular value at which maximum economy obtains, as will be shown.

O A = kVA of load before connection.
O B = „ „ „ after „
O C = kW of load — constant.
O d = Condenser kVA — $o\ a - o\ b$.

(From Fig. 305.)

Reduction in kVA = O A — O B
= kW sec. ϕ_1 — kW sec. ϕ_2.

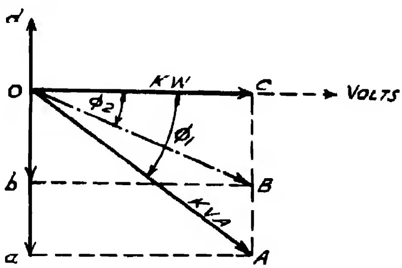


FIG. 305. Power factor correction-constant kW.

If £x is the cost per annum per kVA of maximum demand ; reduction of maximum demand charge per annum

$$= x \,.\, \text{kW} \; (\sec.\phi_1 - \sec.\phi_2)$$

kVA rating of power factor improvement plant

$$= o\,a - o\,b$$
$$= \text{kW} \tan \phi_1 - \text{kW} \tan \phi_2$$
$$= \text{kW} (\tan \phi_1 \quad \tan \phi_2)$$

If £y be the annual interest and depreciation charge on each kVA of improvement plant, then total annual charge for this = y . kW . (tan ϕ_1 — tan ϕ_2).

Nett annual saving S = x . kW . (sec. ϕ_1 — sec. ϕ_2) — y . kW . (tan ϕ_1 — tan ϕ_2).

This is a maximum when $\dfrac{dS}{d\phi_2} \quad 0.$

i.e., when

$$- x \,.\, \text{kW} \,.\, \sec.\phi_2 \tan \phi_2 + y \,.\, \text{kW} \,.\, \sec^2 \phi_2 = 0.$$

from which

$$\text{Sin } \phi_2 = \frac{y}{x}$$

The most economical power factor under constant kW load is given by

$$\text{P.F.} = \sqrt{1 - \sin^2 \phi_2}$$
$$= \sqrt{1 - \left(\frac{y}{x}\right)^2}$$

An alternative method (constant kW) of estimating kVA of necessary phase advancing plant is :

$$\left(\sqrt{1 - \phi_1^2} - \frac{\phi_1}{\phi_2} \cdot \sqrt{1 - \phi_2^2}\right) \cdot \text{P}.$$

Where P is the original kVA.

In practice, the constant kVA condition is also used, in which case an increase of load is met by improving the system power factor so that the additional load can be given without increasing the original kVA demand. The economic limit of power factor is reached when the cost of the phase advancing plant, to produce a given increase in true power, is equal to the cost of generating plant to give the same increase in power.

If P = kVA of station plant or load ;
Cos ϕ_1 = initial power factor ;
Cos ϕ_2 = improved power factor ;
then increase in true power = P (cos ϕ_2 — cos ϕ_1) ;
kVA of phase advancing plant (constant kW) = P (sin ϕ_1 — sin ϕ_2).

A sub-station having a capacity of 1,000 kVA supplied a load with a lagging power factor of 0·71. Calculate the necessary leading kVA of phase advancing plant to raise the sub-station power factor to 0·87 when loaded to maximum output.

This is a condition of constant kVA, and the values of true power and leading kVA are shown in Fig. 306.

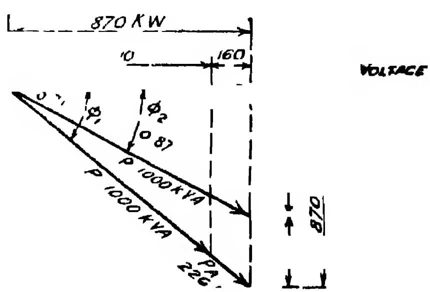


FIG. 306.

The increase in true power $= P(\cos\phi_2 - \cos\phi_1)$;

$= 1{,}000\,(0{\cdot}87 - 0{\cdot}71)$;

$= 160$ kW ; $P_A = \dfrac{160}{0{\cdot}71}$ kVA.

Total kW load $= (1{,}000 \,.\, 0{\cdot}71) + 160$

$= 870$, which now has to operate at a power factor of $0{\cdot}87$ lagging.

kVA of necessary phase advancing plant =

$$(P + P_A)\sin\phi_2 - P \,.\, \sin\phi_1$$

$$\left(1{,}000 + \frac{160}{0{\cdot}71}\right) . \, 0{\cdot}71 - 1{,}000 \,.\, 0{\cdot}5$$

$$= 870 - 500$$

$$= 370 \text{ kVA approximately.}$$

Alternatively :

is given by kW $(\tan\phi_1 - \tan\phi_2)$

$$= 870\,(0{\cdot}97 - 0{\cdot}56)$$

$$= 360 \text{ kVA.}$$

As a further check :

$$\left(\frac{\phi_1}{\phi_2}\sqrt{(1 - \phi_1^2)} - \sqrt{(1 - \phi_2^2)}\right) . \, P.$$

$$= \frac{0{\cdot}87}{0{\cdot}71}\,(1 - 0{\cdot}71^2 - (1 - 0{\cdot}87^2)\,) \,.\, 1{,}000.$$

$$= 360 \text{ kVA.}$$

A system is working at its maximum kVA capacity with a lagging p.f. of $0{\cdot}71$. An anticipated increase of load could be met by :

(1) Raising the p.f. of the system to $0{\cdot}87$ by the installation phase advancers.

(2) By installing extra generating plant, cables, etc., to meet the increased power demands.

The total cost for the latter method is £8 per kVA.

Estimating the limiting cost per kVA of phase advancing plant which would justify its use.

The increase in true power per kVA

$$= P(\cos\phi_2 - \cos\phi_1)$$

$$= 1\,(0{\cdot}87 - 0{\cdot}71)$$

$$= 0{\cdot}16 \text{ kW approximately.}$$

The kVA of phase advancing plant required

$$= (P + P_A) \sin \phi_2 - P \sin \phi_1$$
$$= \left(1 + \frac{0\cdot16}{0\cdot71}\right) . 0\cdot71 - (1 . 0\cdot5)$$
$$= 0\cdot87 - 0\cdot5$$
$$= 0\cdot37 \text{ per kVA of load.}$$

The additional load is 0·16 kW per kVA of load, and if this were met by generating plant operating at 0·71 p.f., then additional kVA required

$$= \frac{0\cdot16}{0\cdot71} = 0\cdot226$$

this would cost £8 per kVA

$\therefore$ total cost $= 0\cdot226 . 8$.

By using phase advancing plant the necessary kVA of such plant to meet this increase, and operating at a p.f. of 0·87, would be 0·37 per kVA of load, and the limiting cost would therefore be, say, x£.

$$\therefore 0\cdot226 . 8 = 0\cdot37 . x$$
$$x = \frac{0\cdot226 . 8}{0\cdot37} = £4\cdot9 \text{ per kVA.}$$

A load of 500 H.P. is to be shared between induction motors operating at 0·8 p.f., and synchronous motors operating at such p.f. that the resultant p.f. is 0·95 lagging. The synchronous motors are to carry 100 H.P. of mechanical load. Estimate their total kVA rating.

Total load 500 H.P. at, say, 92 per cent. efficiency.

$$\therefore \text{input} = 500 . \frac{100}{92} . 0\cdot746 = 406 \text{ kW.}$$

$$\text{Cos } \phi = 0\cdot95 \text{ lagging}$$

$$\therefore \text{Total kVA of this load} = \frac{405}{0\cdot95} = 428 \text{ kVA approximately.}$$

$$\text{Wattless component} = P . \sin \phi$$
$$= 428 . 0\cdot309$$
$$= 132 \text{ kVA.}$$

Likewise $500 - 100 = 400$ H.P. of induction motors at, say, an efficiency of 90 per cent.

$$\therefore \text{input} = 400 . \frac{100}{90} . 0\cdot746 = 330 \text{ kW.}$$

$$\text{Cos } \phi = 0\cdot8 \text{ lagging}$$

$$\therefore \text{ Total kVA of this load} = \frac{330}{0 \cdot 8} = 413 \text{ kVA.}$$

$$\text{Wattless component} = 413 \, . \, 0 \cdot 6$$
$$= 248 \text{ kVA}$$

Leading wattless kVA to be given by synchronous motors

$$= 248 - 132$$
$$= 116 \text{ kVA.}$$

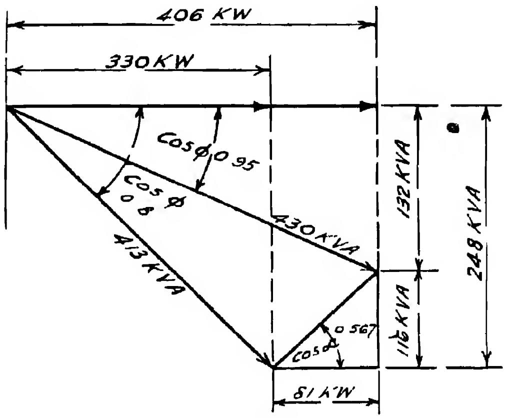


FIG. 307.

In addition, these motors supply 100 H.P.

$$\therefore \text{ True power} = 100 \, . \, \frac{100}{92} \, . \, 0 \cdot 746 = 81 \text{ kW}$$

$$\therefore \text{ Total kVA rating} = \sqrt{(81^2 + 116^2)}$$
$$= 143 \text{ kVA approximately.}$$

$$\text{Cos } \alpha, \text{ p.f. of synchronous motors} = \frac{81}{143} = 0 \cdot 567.$$

$$\text{Total kVA of resultant load} = \frac{330 + 81}{0 \cdot 95}$$
$$= 430 \text{ approximately}$$

(428 before).

The vector relationships are shown in Fig. 307.

A sub-station supplies an inductive load of 5,000 kW at a p.f. of 0·7 lagging by means of a three-phase, 50-cycle, overhead line 5 miles long, with conductors symmetrically arranged. The resistance per mile of each conductor is 0·61 ohm, and the self-induction per mile of loop formed by two of the conductors taken together is 0·0035 henry. The voltage at the receiving end is maintained constant at 10 kV. If a static condenser is connected across the load to increase the p.f. at the receiving end from 0·7 to 0·9, calculate :

(*a*) the value of the capacity per phase of the condenser ;

(*b*) the sub-station voltage with the condenser in ;

(*c*) „ „ „ „ „ „ out.

$$0{\cdot}7 \text{ p.f.} = \frac{5{,}000 \,.\, 1{,}000}{\sqrt{3} \,.\, 10{,}000 \,.\, 0{\cdot}7} = 414 \text{ amps.}$$

$$\text{I } 0{\cdot}9 \text{ p.f.} = \frac{5{,}000 \,.\, 1{,}000}{\sqrt{3} \,.\, 10{,}000 \,.\, 0{\cdot}9} = 320$$

From Fig. 308. $C^2 = a^2 + b^2 - 2 \,.\, a \,.\, b \,.\, \cos \alpha$

$= 414^2 + 320^2 - 2 \,.\, 414 \,.\, 320 \,.\, 0{\cdot}942$

$C = \sqrt{24{,}300}$

$= 156$ amps. $=$ Ic conductor charging current.

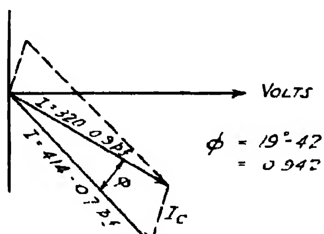


FIG. 308.

Since the charging current Ic per conductor $= 2\pi f.C\dfrac{E_L}{\sqrt{3}}$

$$\therefore C = \frac{156 \,.\, 10^6 \,.\, \sqrt{3}}{2\pi \,.\, 50 \,.\, 10{,}000}$$

$= 86$ microfarads.

∴ Capacity per phase if star-connected $= 86$ mfds.

(*a*) „ „ „ „ delta-connected $= \dfrac{86}{3} = 28{\cdot}7$ mfds.

Voltages at sub-station end by approximate method :

(*b*) :
$$E = V + (IR\cos\phi + IX\sin\phi).$$
$$= 10{,}000 + (320 \,.\, 3{\cdot}05 \,.\, 0{\cdot}9 + 320 \,.\, 5{\cdot}5 \,.\, 0{\cdot}43)\sqrt{3}$$
$$= 10{,}000 + (880 + 760)\sqrt{3}$$
$$= 12{,}840 \text{ volts approximately.}$$

$$R = 0{\cdot}61 \,.\, 5$$
$$= 3{\cdot}05 \text{ ohms.}$$
$$X = 2\pi f L.$$
$$= 2\pi \,.\, 50 \,.\, 0{\cdot}0035 \,.\, 5$$
$$= 5{\cdot}5 \text{ ohms.}$$

(*c*)
$$E = 10{,}000 + (414 \,.\, 3{\cdot}05 \,.\, 0{\cdot}7 - 414 \,.\, 5{\cdot}5 \,.\, 0{\cdot}71)\sqrt{3}$$
$$= 10{,}000 + (865 + 1{,}620)\sqrt{3}$$
$$= 14{,}300 \text{ volts approximately.}$$

Sub-station Plant Economics. When considering the installation of any plant—apart, perhaps, from switchgear—an engineer will find that there are generally two or more different propositions before him and it is necessary for him to decide whether it will pay him financially to spend extra capital to reduce the annual charges. Most plant has its total cost divided into two sections—Capital costs and Running costs, and the total annual charges is the sum of these. Capital costs include interest and depreciation, while Running costs include the cost of electrical energy consumed and the maintenance charges. Taking the ordinary view of capital costs, these can be expressed as :

$$C = \left(O \,.\, \frac{r}{100}\right) + \left(\frac{O}{n}\right) \text{ £ per annum.}$$

Where O = original or first cost of plant ;
r = rate of interest on capital, per cent. ;
n = number of years, useful life.

The interest charge is calculated without including the annual reduction in value due to depreciation, which is provided for separately. The depreciation charge is obtained by dividing the first cost by the number of years' useful life. This assumes no salvage value. Various methods are used for estimating the depreciation allowance, and in the straight line law (same contribution set aside each year) :

$$D = \left(\frac{O - R}{n}\right) \text{ £ per annum ;}$$

where D = depreciation contribution per annum, £.
O = as before.
R = residual value of plant or buildings at end of "n" years in £.

In municipal work, the maximum period for paying off plant is 20 years, whereas cables need not be paid off until 25 to 40 years (untapped feeders) after installation. Assuming interest on capital at 5 per cent. per annum, and sinking fund contributions at 3 per cent. (net), the total annual charges for a 20-year life are 8·72 per cent., compared with 7·1 per cent. for 30 years. Basing calculations on the annual costs instead of the total cost makes but little difference to the final result. In any economic problem some of the costs (original cost) occur once per lifetime of the plant, while other costs (running and losses) occur annually. To make a comparison it is necessary either to capitalise or "annualise" the capital costs. The "rate of capitalisation" refers to the rate or coefficient by which an annual cost can be multiplied to convert it into its equivalent capital cost, or its present value. The term "capitalisation" in effect means converting the recurring annual charges into a single capital sum which if spent now is the present value of all the subsequent annual charges during the life period of the transformer. As an example, a transformer incurs losses costing £20 each year over a given life of 20 years ; the rate of interest is 5 per cent., and the depreciation charge 2·94 per cent. (based on a 20-year sinking fund, with quarterly payments and interest at 5 per cent.). A capital sum could be "annualised" by multiplying it by (5 + 2·94), *i.e.*, 7·94, and thus spread it over the years of the life of the plant. Alternatively, an annual sum could be capitalised by multiplying by the reciprocal of this : $\frac{100}{7 \cdot 94} = 12 \cdot 6$. A sum of £20 per annum for 20 years is therefore the equivalent of a capital sum of £352, and it would be justifiable to spend anything up to this amount in order to save these losses. The examples given will serve to illustrate the applications of this procedure to substation plant.

A supply authority with an A.C. system has to install additional sub-stations for feeding a D.C. network, and tenders for plant are :

(*a*) Motor generators at £2·9 per kW.

(*b*) Rotary convertors and transformers at £3·2 per kW ; 33 per cent. of spare plant is necessary in each case. Switchgear and other costs are the same. If the respective efficiencies of the machines are 84 and 89 per cent. at the average load throughout the year, which machine will give the more economic production ? Capital charges, 12½ per cent. per annum. Cost of H.V. energy, 0·45*d.* per unit.

(*a*) : $\dfrac{1 \,.\, 8{,}760 \,.\, 0{\cdot}45 \,.\, 0{\cdot}5}{0{\cdot}84 \,.\, 240}$ = £9·75 per kW per annum at 50 per cent. load factor.

£2·9 per kW + 33 per cent. spare
= 2·9 + 0·966
= £3·8 per kW per annum capital cost.

Capital charges on £3·8 at 12½ per cent. = £0·476 per kW per annum.

Total = £10·226 ,, ,, ,, ,,

(*b*) : $\dfrac{1 \,.\, 8{,}760 \,.\, 0{\cdot}45 \,.\, 0{\cdot}5}{0{\cdot}89 \,.\, 240}$ = £9·22 ,, ,, ,, ,,

£3·2 + 33 per cent.
= £4·26

Capital charges at 12½ per cent. = £0·533 ,, ,, ,, ,,

Total = £9·753 ,, ,, ,, ,,

∴ Saving per kW per annum
= £10·226 − £9·753.
= £0·473 in favour of rotary convertor at 50 per cent. load factor.

Choice of Converting Plant. The choice is usually limited to rotary convertors, motor convertors, and rectifiers, and, in the example under consideration, it is assumed for the purpose of comparison that 750 kW of plant is required for traction service. The existing system plant capacity in the outlying sub-stations is sufficient to meet present requirements with all units in commission, but reliance for stand-by is placed on plant at a central sub-station which, owing to its distance from the feeding points, and consequent voltage drop, is not entirely satisfactory. The question of traction supplies is becoming important with the speeding up of the trams, and the high power requirements of railless vehicles, together with the effect of heavy gradients, and the existence of railless systems at the extremities of the traction network render it necessary to consider extensions to existing sub-stations.

The assumed tenders received are :

	Efficiencies (per cent.)				
	$\frac{1}{4}$ OL	FL	$\frac{3}{4}$ FL	$\frac{1}{2}$ FL	P.F.
Motor convertor	92·0	92·3	92·1	90·9	1·00
Rotary convertor	94·0	93·8	93·0	91·2	0·98
Rectifier (steel tank)	93·8	94·2	94·7	94·6	0·98

Costs		*Overload Capacities*	
M.C.	£4,600	25 per cent.	2 hours.
R.C.	£4,300	50 ,, ,,	15 minutes.
R.	£3,000	100 ,, ,,	15 seconds.

Speeds

M.C. . 750 r.p.m. The other differences are set out in Table 25.

R.C. . 1,000 ,, Allow annual capital charges of 8 per cent.

The loading is estimated at 600 kW for 2 hours and 300 kW for 15 hours on weekdays, and 14 hours on Sundays. At 300 kW the efficiencies of the M.C. and R.C. are about the same.

Units output at 600 kW are :

$$600 \cdot 2 \cdot 6 \cdot 52 = 374{,}400 \text{ per annum.}$$

Input to motor convertor at 92·2 per cent. efficiency	406,000 units.
,, ,, rotary ,, ,, 93·2 ,, ,, ,,	= 401,000 ,,
Additional losses of M.C.	5,000 ,,

Taking cost of losses at 0·25 pence per unit, this amounts to an annual charge of $\frac{0 \cdot 25 \cdot 5{,}000}{240} = £5 \cdot 2$ in favour of R.C.

Assuming 20 years loan period, with interest and sinking fund at 8 per cent., this represents a capital sum of :

$$5 \cdot 2 \cdot \frac{100}{8} = £65 \text{ in favour of R.C.}$$

Capitalised value of additional maintenance charges in respect of R.C. and not M.C. :

	£	*Cost per annum.* £
Filtering of transformer oil every 5 years . .	35	
Complete change of oil after, say, 10 years . .	68	
	103	10·3
Slip-ring maintenance ; one set of brushes every 2 years	14	
Labour in setting	2	
	16	8·0
Other ring maintenance, etc.		10·0
Total . .		£28·3

The D.C. commutator and brush gear maintenance is usually less on M.C.'s, and it is assumed that this balances the small cost of slip-ring maintenance on M.C. The annual charge on £28·3 at 8 per cent. therefore represents a capital saving of £350 in favour of M.C. Another advantage of the M.C. is that its speed (750 r.p.m.) is less than R.C. (1,000 r.p.m.), and it is reasonable to expect it to be a quieter running machine.

The M.C. will now be compared with the rectifier, and it is assumed that the efficiencies given include all auxiliaries. With the loadings as before, the units output at 300 kW are :

$$300 \,.\, 15 \,.\, 6 \,.\, 52 = 1{,}400{,}000 \text{ units.}$$
$$300 \,.\, 14 \,.\, 1 \,.\, 52 = 219{,}000 \text{ ,,}$$
$$1{,}619{,}000 \text{ ,,}$$

Input to M.C. at 89 per cent. efficiency = 1,820,000 units.
,, ,, R. ,, 94 ,, ,, ,, = 1,720,000 ,,

Reduction of losses in favour of R. = 100,000 ,,

Taking cost of losses at 0·25 pence per unit, this amounts to an annual charge of : $\frac{0{\cdot}25 \,.\, 100{,}000}{240} = £104$ in favour of R.

Similarly at 600 kW :

Input to M.C. for 374,400 units	= 406,400 units.
Input to R. for 374,400 units at 94·65 per cent. efficiency	= 396,000 ,,
Reduction of losses in favour of R.	= 10,400 ,,

which corresponds to an annual charge of : $\frac{0{\cdot}25 \,.\, 10{,}400}{240} = £10{\cdot}8.$

Therefore the total reduction in losses due to the improved efficiency of the rectifier is represented by an annual charge of £104 + £10·8 × £114·8 in favour of rectifier.

The rectifier requires a cooling water supply, for which allowance must be made. Taking 0·4 gallon per minute (24 per hour) for vacuum pump, and 0·15 gallon per minute (120 per hour) per 100 amps. D.C. output for anode cooling water. If water is on continuously, this would mean an annual consumption of 1,260,000 gallons, the charges for which would be :

	£
Rent	5
First 400,000 gallons at 1*s*. 1½*d*. per 1,000 galls. .	23
860,000 gallons at 11¼*d*. per 1,000 galls. . .	40
Total . . .	£68 approx.

Arrangements could be made to reduce the consumption by shutting off water when the rectifier was not in service. Assuming 17 hours water service per day, the consumption would be about 900,000 gallons per annum, and the resulting cost would be :

	£
Rent	5
First 400,000 gallons at 1*s*. 1½*d*. per 1,000 galls. .	23
500,000 gallons at 11¼*d*. per 1,000 galls. . .	23
Total . .	£51

	£
The annual charges in favour of rectifier	114·8
Less amount due to water charges	51·0
Reduction in favour of rectifier as compared with M.C.	£63·8

This amount at 8 per cent. per annum represents a capital sum of:

$$63{\cdot}8 \cdot \frac{100}{8} = £790 \text{ in favour of rectifier.}$$

Assuming maintenance to be similar to rotary convertor in respect of transformer, and making allowance for auxiliaries, etc., say, £15, representing a capital sum of £180.

TABLE 25. *Comparative Costs*

750 kW. unit, fully automatic	Motor convertor £	Rotary convertor £	M.A. rectifier £
Cost including erection . .	4,600	4,300	3,000
6·6 kV. switchgear . . .	450	450	450
550 v. D.C. switchgear . .	400	400	400
Cabling and cables . . .	70	150	250
Foundations	200	300	100
Water service, and coolers . .	—	—	350
Air filter	100	100	—
Capitalised value of comparative losses	65	—	Less 790
Capitalised value of comparative maintenance	—	350	180
Total . £	5,885	6,050	3,940

Table 25 shows the comparative costs, and the total annual charges are tabulated in Table 26.

TABLE 26. *Annual Charges*

	Motor convertor £	Rotary convertor £	M.A. rectifier £
Capital charges at 8 per cent.	465 6	456·0	364·0
Comparative cost of losses	5·2	—	Less 63·8
Comparative cost of maintenance	—	28·3	15·0
Total £	470·8	484·3	315·2

It will be noted that no allowance has been made for building costs, but, generally speaking, the rectifier will show a saving in space required.

Capitalisation of Transformer Prices and Losses. There are several methods of doing this, and the following will serve to indicate the manner of approach.

Consider that an 800 kVA transformer is required, and four offers are available, viz (Table 27) :

TABLE 27

Transformer	Cost £	Iron loss kW	Full load copper loss kW	Remarks
Lowest efficiency, "A"	450	3·08	9·60	
Medium efficiency, "B"	475	2 80	8 50	More than "A" by £25. I, less than "A" by 0 28 kW. C, ,, ,, ,, ,, 1 10 ,,
Higher efficiency, "C"	506	2·60	7 90	More than "A" by £56. I, less than "A" by 0 48 kW. C, ,, ,, ,, ,, 1 70 ,,
Extra "D"	480	2·60	8 70	More than "A" by £30. I, less than "A" by 0·48 kW. C, ,, ,, ,, ,, 0 90 ,,

Method 1 (Table 28) :

(*a*) Capital charges . . . 8 per cent. per annum.
(*b*) Iron and fixed losses . . £7·3 per kW per annum.
(*c*) Copper losses . . . £1·72 ,, ,, ,, ,,

$$\text{the cost of iron loss} = \frac{8\cdot760 \,.\, 0\cdot2}{240} = £7\cdot3.$$

$$,, \quad ,, \quad ,, \text{copper} \quad ,, = \frac{8\cdot760 \,.\, 0\cdot2 \,.\, 0\cdot236}{240} = £1\cdot72.$$

0·2*d.* per unit.
23·6 per cent. load factor.

TABLE 28

Transformer	A	B	C	D
	£	£	£	£
Capital charges .	36·0	38·0	40·0	38·4
Fixed losses . .	22·4	20·4	19·0	19·0
Copper losses . .	16·5	14·6	13·6	15·0
Total annual charges £	74·9	73·0	73·0	72·4

Method 2 :

Total annual charges = £(0·08 C + 1·82 W).
C = capital cost in £.
W = losses at full load, kW.

		£
A	(36 + 23)	= 59·0
B	(38 + 20·6)	= 58·6
C	(40·4 + 19·1)	= 59·5
D	(38·4 + 20·6)	= 59·0

Method 3 (Table 29) :

On the basis of the lowest efficiency transformer.

TABLE 29

Transformer		B	C	D
Difference in fixed losses	kW	0·28	0·48	0·48
Difference in copper losses	kW	1·10	1·70	0·90
Fixed losses saved per annum (100 per cent. L.F.)	kWh	2,460	4,200	4,200
Saving on fixed losses per annum at 0·15*d.* per unit	£	1·53	2·62	2·62
Copper losses saved per annum (30 per cent. L.F.)	kWh	2,900	4,450	2,360
Saving on copper losses per annum at 0·15*d.* per unit	£	1·81	2·78	1·48
Total annual saving on losses . .	£	3·34	5·40	4·1
Less annual charge on extra cost	£	2·00	4·48	2·4
Net annual saving . .	£	1·34	0·92	1·7

By using transformer "D," instead of "A," the net annual saving on losses alone (unit charge) would be £1·7. Capitalised value of losses at 8 per cent. $= 4 \cdot 1 \cdot \frac{100}{8} = £51 \cdot 4$.

The cash value of the saving of losses by purchasing transformer "D" would be about £51·4 − 30 = £21·4 ; or $£1 \cdot 7 \cdot \frac{100}{8} = £21 \cdot 2$ approx.

Method 4 :

Assuming :

(*a*) Capital charges . . 8 per cent. per annum.

(*b*) Iron and fixed losses } see below.
(*c*) Copper losses }

Cost of electrical energy is £3·5 per kVA plus 0·2 pence per unit. Ratio of average kVA load to kVA capacity of transformer is 0·4. Ratio of kVA demand on transformer (at time of system maximum demand) to transformer kVA is 0·75.

$$\text{Then } b = \frac{8{,}760 \cdot 0{\cdot}2}{240} + 3{\cdot}5 = £10{\cdot}8 \text{ per kVA}$$

$$\left.\frac{8{,}760 \,.\, 0{\cdot}2 \,.\, 0{\cdot}28}{240}\right) + (0{\cdot}562 \,.\, 3{\cdot}5) \; (0{\cdot}75^2 = 0{\cdot}562)$$
$$= £4{\cdot}01 \text{ per kVA.}$$

Load factor of losses = $(0{\cdot}5 + 0{\cdot}5F^2)$

Where F = load factor (see D. J. Bolton, "Electrical Engineering Economics").

$= (0{\cdot}5 \,.\, 0{\cdot}4) + (0{\cdot}5 \,.\, 0{\cdot}4^2)$

$= 0{\cdot}28.$

Taking two transformers, 750 and 1,500 kVA, respectively, with different losses the equivalent figures would be as given in Table 30.

TABLE 30

Transformer, KVA	750			1,500		
Alternative tenders :	1	2	3	1	2	3
Cost . . £	605	628	660	987	1,030	1,080
Iron loss . . kW	2·93	2·5	2·5	5·0	4·3	4·3
Copper loss . kW	9·2	9·2	7·8	14·3	14·3	12·2
(*a*) . £	48·5	50·3	52·8	79·0	82·5	86·5
(*b*) . . £	31·6	27·0	27·0	54·4	46·4	46·4
(*c*) . £	36·9	36·9	31·4	57·4	57·4	48·9
Total annual charges £	117·0	114·2	111·2	190·8	186·3	181·8

The copper loss values are taken at 75° C., which is on the high side, for comparison. While reducing losses show a reduction in the annual charge, there is a limit to which these may be taken, as the increase in first cost rises exponentially.

Oil Filtering Plant. The annual capital charges are relatively small and the running costs can in most cases be neglected.

If P = cost of new oil per gallon, £.
Q = " " filtering plant, £.
L = useful life of oil in years.
R = rate of interest, per cent.

Assuming life of filter plant to be 20 years

$$\therefore \text{ Annual cost of filter plant} = \frac{Q}{20} \quad \frac{QR}{100}$$

Annual quantity of oil filtered which would equal annual cost of filter plant,

$$A = \frac{Q}{20} + \frac{QR}{100} \Big/ \frac{P}{L}$$

$$\text{or } Q = L \frac{\left(\frac{5Q + QR}{100} \right)}{P}$$

Filter plant cost £250 ; oil 4*s*. 6*d*. per gallon ; oil life 5 years and an interest of 3 per cent.

$$A = 5 \frac{\left(\frac{5 \,.\, 250 + 250 \,.\, 3}{100} \right)}{4 \cdot 5/20} = 444 \text{ gallons.}$$

Cable Selection. Economic considerations determine the optimum size of cable conductor, whereas thermal considerations, normal current and short circuit current, together with permissible voltage drop fix the minimum conductor size.

The factors involved are : (1) voltage drop, (2) normal current rating, (3) short circuit current rating, (4) economic considerations. The I.E.E. Regulations and Cable Manufacturers' Handbooks deal with (1) and (2), and (3) is referred to in Chapters IV and V.

Referring to (4), this is summarised by Kelvin's Law, which states that " The most economical size of copper conductor for the electrical transmission of energy will be found by comparing the annual interest of the money value of the copper with the money value of the energy lost annually in the heat generated in it by the electric current." Incorrect assumption that the cost of a main is proportional to the weight of the conductors.

When planning transmission and distribution systems it is desirable that cable sizes should be standardised, for considerable savings can be effected in stocks, stores records, costing, joint boxes, etc.

Determine the most suitable cross-section for a two-wire feeder cable, 500 yards long, from the following considerations :

Cross-section area, in.^{2} . .	0·10	0·15	0·20	0·25	0·30
Resistance in ohms per 1,000 yards	0·245	0·167	0·126	0·10	0·081
Cable cost . . . . £	275	300	330	375	460
Safe current . . amps	155	200	240	278	313

Current, 175 amps. ; interest and depreciation, 10 per cent. ; cost of energy wasted, 1*d.* per unit, the loss being such as would be produced by 175 amps. for 4 hours per day.

$$\text{Copper losses} = I^2R \text{ watts.}$$

$$\text{Cost of losses} = \frac{I^2R}{1{,}000} \cdot 1 \text{ pence per hour.}$$

$$= \frac{I^2R \cdot 1}{1{,}000 \cdot 240} \text{ £ per hour,}$$

and since 175 amps. are used for 4 hours per day, the cost of copper losses per year is :

$$\frac{175^2 \cdot R \cdot 1 \cdot 4 \cdot 365}{1{,}000 \cdot 240} = 186 \text{ R £ per year.}$$

		£
0·10 in.^{2} cable . Copper loss	= 186 . 0·245 =	45·5
0·15 ,, ,, . ,, ,,	= 186 . 0·167 =	31·0
0·20 ,, ,, . ,, ,,	= 186 . 0·126 =	23·4
0·25 ,, ,, . ,, ,,	= 186 . 0·100 =	18·6
0·30 ,, ,, . ,, ,,	= 186 . 0·081 =	15·0

0·10 in.^{2} cable . Total annual loss	= 45·5 + 27·5 = 73·0
0·15 ,, ,, . ,, ,, ,,	= 31·0 + 30·0 = 61·0
0·20 ,, ,, . ,, ,, ,,	= 23·4 + 33·0 = 56·4
0·25 ,, ,, . ,, ,, ,,	= 18·6 + 37·5 = 56·1
0·30 ,, ,, . ,, ,, ,,	= 15·0 + 46·0 = 61·0

The 0·25 in.^{2} cable has the least total of annual losses, and would therefore be selected subject to certain other factors.

Transformers. A 25 kVA 2,000/200-volt transformer has iron and copper losses of 350 and 400 watts, respectively. Calculate the efficiency at F.L. and $\frac{1}{2}$ F.L. at unity p.f. and at 0·8 p.f. Determine load which gives maximum efficiency.

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Iron loss} + \text{Copper loss}}.$$

$$= \frac{25 \cdot 1{,}000}{25 \cdot 1{,}000 + 350 + 400} \cdot 100$$

$$= 97{\cdot}5 \text{ per cent. at F.L. and unity p.f.}$$

Now copper loss is $\propto I^2$

$$\tfrac{1}{2}\text{ F.L.} = \tfrac{1}{4}\text{ F.L. copper loss}$$

$$= \frac{400}{4} = 100 \text{ watts.}$$

$$\text{Efficiency} = \frac{12{\cdot}5 \,.\, 1{,}000}{12{\cdot}5 \,.\, 1{,}000 + 350 + 100} \,.\, 100$$

$$= 96{\cdot}5 \text{ per cent at } \tfrac{1}{2} \text{ F.L. and 1 p.f.}$$

$$\text{Efficiency} = \frac{25 \,.\, 1{,}000 \,.\, 0{\cdot}8}{25 \,.\, 1{,}000 \,.\, 0{\cdot}8 + 350 + 400} \,.\, 100$$

$$= 96{\cdot}5 \text{ per cent at F.L. and } 0{\cdot}8 \text{ p.f.}$$

$$\text{Efficiency} = \frac{12{\cdot}5 \,.\, 1{,}000 \,.\, 0{\cdot}8}{12{\cdot}5 \,.\, 1{,}000 \,.\, 0{\cdot}8 + 350 + 100} \,.\, 100$$

$$= 95{\cdot}7 \text{ per cent. at } \tfrac{1}{2} \text{ F.L. and } 0{\cdot}8 \text{ p.f.}$$

The maximum efficiency occurs when the copper loss equals the iron loss.

$$W_c = W_i$$

$$I^2R = W_i$$

$$I_m^2 \frac{400}{125^2} = 350$$

$$I_m = 117 \text{ amps.}$$

$$I_S = \frac{25 \,.\, 1{,}000}{200}$$

$$= 125 \text{ amps.}$$

$$I_S^2R = 400$$

$$R = \frac{400}{125^2}$$

$$\text{Load for maximum efficiency} = \frac{117 \,.\, 200}{1{,}000}$$

$$= 23{\cdot}4 \text{ kVA approx.}$$

Alternatively :

$$\text{Maximum efficiency loading} = \text{kVA} \,.\, \sqrt{\frac{W_i}{W_c}}$$

$$= 25 \,.\, \sqrt{\frac{350}{400}}$$

$$= 25 \,.\, 0{\cdot}935$$

$$= 23{\cdot}4 \text{ kVA.}$$

When comparing offers for transformers, care should be taken to ascertain that performance data are computed to the same reference temperature. B.S.S.171—1936 gives 75° C., whereas manufacturers base the losses on a reference temperature of 15° C. This gives reduced copper losses, and consequently higher efficiencies.

Ratio $\frac{Wi}{Wc}$		Load at which maximum efficiency occurs %.
1 : 4	—	50
1 : 1·78	—	75
1 : 1	—	100

250 kVA, three-phase, 50-cycle, 11,000/400-volt transformer.

Copper loss . 3,750 watts – 1·5 per cent. } 250 kW p.f. unity.
Iron loss . 1,250 „ – 0·5 „ „ }

5,000 „ Reactance, 4·98 per cent.

Efficiency at unity p.f. :

$$\text{Full load efficiency} = \frac{\text{Output in watts}}{\text{Output in watts} + \text{total loss in watts}} \cdot 100$$

$$= \frac{250{,}000 \cdot 100}{250{,}000 + 5{,}000} = 98 \text{ per cent.}$$

Now kVA . p.f. = kW.

Copper losses per cent. = 1·87. Reactance 4·98.

Iron loss per cent. = 0·62

Efficiency at 0·8 p.f.

$$= \frac{200{,}000 \cdot 100}{200{,}000 + 5{,}000} = 97\cdot5 \text{ per cent.}$$

Regulation. In a standard transformer having a comparatively low reactance, the percentage regulation at unity p.f. is approximately equal to the percentage copper loss. The exact value can be obtained from :

$$\frac{\text{Copper loss} \cdot 100}{\text{output}} + \frac{(\text{per cent. reactance})^2}{200}$$

(*Note.* The 200 is derived by an approximation in calculations.)

Let E_1 and E_2 be open circuit and full load voltages respectively. Let E_R and E_X be the actual components of voltage drop due to resistance and reactance. Then in the case of unity power factor

$$E_1^2 = (E_2 + E_R)^2 + E_X^2$$
$$= E_2^2 + 2E_2 . E_R + E_R^2 + E_X^2$$
$$\therefore E_1^2 - E_2^2 = 2E_2 . E_R + E_R^2 + E_X^2$$

Factorising and transposing

$$E_1 - E_2 = \frac{E_R . (2E_2 + E_R)}{E_1 + E_2} + \frac{E_X^2}{E_1 + E_2}$$

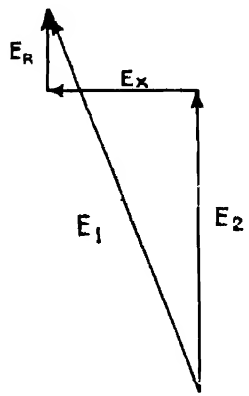


FIG. 309

By approximation, if E_1 and E_2 do not differ greatly and ER is comparatively small (Fig. 309) :

$$E_1 - E_2 \simeq E_R + \frac{E_X^2}{2E_1}$$
$$\frac{E_1 - E_2}{E_1} \simeq \frac{E_R}{E_1} + \frac{E_X^2}{2E_1^2}$$
$$\frac{100\,(E_1 - E_2)}{E_1} \simeq \frac{100\,E_R}{E_1} + \frac{100\,E_X^2}{2E_1^2}$$
$$\simeq 100\,\frac{E_R}{E_1} + \left(\frac{100\,E_X}{E_1} . \frac{100\,E_X}{E_1} . \frac{1}{200}\right)$$

$$\text{or Regulation} = \%\ \text{resistance voltage} + \frac{(\%\ \text{reactance voltage})^2}{200}$$

$$= \frac{3{,}750 \cdot 100}{250{,}000} + \frac{(4 \cdot 98)^2}{200}$$
$$= 1 \cdot 5 + 0 \cdot 124$$
$$= 1 \cdot 624 \text{ per cent. at 1 p.f.}$$

To obtain the regulation at power factors other than unity, the formula :

$$R \cos \phi + X \sin \phi + \frac{(X \cos \phi - R \sin \phi)^2}{200} \text{ is used.}$$

$$R - \text{per cent. resistance drop} = \frac{\text{Copper loss} \cdot 100}{\text{Output}}$$

Percentage regulation at $0 \cdot 8$ p.f.

$$1 \cdot 5 \cdot 0 \cdot 8 + 4 \cdot 98 \cdot 0 \cdot 6 + \frac{(4 \cdot 98 \cdot 0 \cdot 8 - 1 \cdot 5 \cdot 0 \cdot 6)^2}{200}$$
$$= 1 \cdot 2 + 2 \cdot 98 + 0 \cdot 047$$
$$= 4 \cdot 23 \text{ per cent.}$$

The impedance can be estimated as follows :

$$Z = \sqrt{R^2 + X^2}$$
$$= \sqrt{1 \cdot 5^2 + 4 \cdot 98^2}$$
$$5 \cdot 1 \text{ per cent.}$$

Parallel Operation. Two transformers are connected in parallel ; the first, of 500 kVA, has a resistance drop of 1 per cent., and a reactance drop of 7 per cent. ; and the second, of 400 kVA, a resistance drop of 3 per cent., and a reactance drop of 5 per cent. If the total load is 800 kVA at $0 \cdot 8$ power factor, estimate the load carried by each transformer.

$$Z_1 = R_1 + jX_1 \qquad Z_2 = R_2 + jX_2$$
$$Z = \frac{Z_1 \cdot Z_2}{Z_1 + Z_2}$$

Since the voltage drop in each transformer must be the same

$$I_1 Z_1 = I_2 Z_2 = IZ$$
$$I_1 Z_1 = I \frac{Z_1 \cdot Z_2}{Z_1 + Z_2} \qquad \therefore \quad I_1 = I \cdot \frac{Z_2}{Z_1 + Z_2}$$

With constant line volts, the kVA can be substituted for current. Resistance and reactance figures must be referred to one base, and choosing 500 kVA, we have :

$$R_2 = 3 \cdot \frac{500}{400} = 3 \cdot 75 \text{ per cent.}$$

$$X_2 = 5 \cdot \frac{500}{400} = 6{\cdot}25 \;\;\text{,,} \quad \text{,,}$$

Now $I = I \cos^{-1} 0{\cdot}8 = I \,\overline{\left| 36^\circ . 54' \right.}$

$$Z_1 = 1 + j7 = 7{\cdot}08 \,\underline{\left| \tan^{-1} 7 \right.} = 7{\cdot}08 \,\underline{\left| 81^\circ . 54' \right.}$$

$$Z_2 = 3{\cdot}75 + j\,6{\cdot}25 = 7{\cdot}28 \,\underline{\left| \tan^{-1} 1{\cdot}666 \right.} = 7{\cdot}28 \,\underline{\left| 59^\circ \right.}$$

$$Z_1 + Z_2 = 4{\cdot}75 + j\,13{\cdot}25 = 14{\cdot}08 \,\underline{\left| \tan^{-1} 2{\cdot}79 \right.}$$

$$= 14{\cdot}08 \,\underline{\left| 70^\circ . 18' \right.}$$

$$I_1 = I \,\overline{\left| 36^\circ\, 54' \right.} \cdot \frac{7{\cdot}28}{14{\cdot}08} \underline{\left| \frac{59^\circ}{70^\circ\, 18'} \right.}$$

$$= 0{\cdot}517\, I \,\overline{\left| 36^\circ\, 54' - 59 + 70^\circ\, 18' \right.}$$

$$= 0{\cdot}517 \,.\, I \,.\, \overline{\left| 48^\circ\, 12' \right.}$$

Substituting kVA for current, then :

$$\text{kVA} = 0{\cdot}517 \,.\, 800 \,.\, \overline{\left| 48^\circ\, 12' \right.} = 414 \text{ kVA at } 0{\cdot}67 \text{ p.f.}$$
$$= 277 \text{ kW.}$$

Similarly,

$$I_2 = I \,\overline{\left| 36^\circ\, 54' \right.} \cdot \frac{7{\cdot}08}{14{\cdot}08} \underline{\left| \frac{81^\circ\, 54'}{70^\circ\, 18'} \right.}$$

$$\therefore I_2 = 0{\cdot}504 \,.\, I \,.\, \overline{\left| 25^\circ\, 18' \right.}$$

$$\text{kVA}_2 = 0{\cdot}504 \,.\, 800 \,\overline{\left| 25^\circ\, 18' \right.}$$
$$= 403 \text{ kVA at } 0{\cdot}9 \text{ p.f.}$$
$$= 362 \text{ kW.}$$

Total output $= 277 + 362 = 639$ kW approx., which is equivalent to 800 kVA at 0·8 p.f. Due to difference in phase the kVA loading does not add arithmetically to the total kVA.

An alternative approximate method may also be used, and the following example illustrates its use :

Two 100-kW single-phase transformers are connected in parallel —one unit has an ohmic drop of ½ per cent. at full load and an inductive drop of 8 per cent. at full load ; the other has an ohmic drop of ¾ per cent., and an inductive drop of 4 per cent. How do they share the following load : 180 kW at 0·9 p.f.

Let I_a = current in transformer A.
„ I_b = „ „ „ B.

The two voltage drops must be equal, *i.e.*,

$$I_a\,(R_a \cos\phi + X_a \sin\phi) = I_b\,(R_b \cos\phi + X_b \sin\phi)$$

$$I_a\,(0{\cdot}5\,.\,0{\cdot}9 + 8\,.\,0{\cdot}436) \qquad I_b\,(0{\cdot}75\,.\,0{\cdot}9 + 4\,.\,0{\cdot}436)$$

$$\frac{I_a}{I_b} = \frac{(0{\cdot}75\,.\,0{\cdot}9 + 4\,.\,0{\cdot}436)}{(0{\cdot}5\,.\,0{\cdot}9 + 8\,.\,0{\cdot}436)} = \frac{2{\cdot}419}{3{\cdot}937} \qquad \text{Total} = 6{\cdot}35.$$

$$\frac{3{\cdot}937}{6{\cdot}35} = 180 = 111{\cdot}5 \text{ kW on B}$$
$$68{\cdot}5 \text{ kW on A.}$$

The graphical solution of such problems is more accurate.

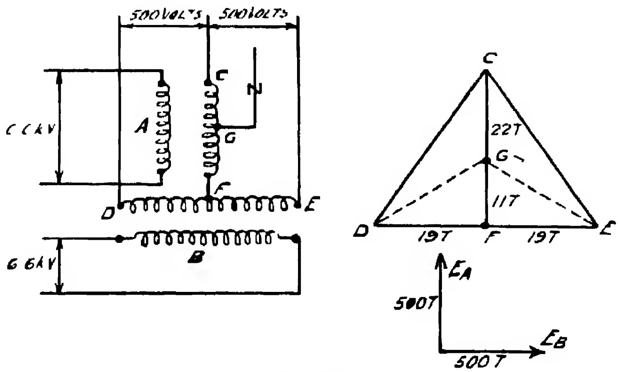


FIG. 310.

Scott and Auto-transformers. A Scott-connected transformer is fed from a 6·6 kV two-phase network, and supplies three-phase power at 500 volts between lines on a three-phase four-wire system. If there are 500 turns per phase on the two-phase side, find the numbers of turns in the low voltage windings and the position of the tapping of the neutral point.

$$\text{Voltage CF} = \frac{\sqrt{3}}{2}\,.\,\text{DE.} \quad \text{(Fig. 310.)}$$
$$= 0{\cdot}866 \text{ DE}$$

The vectors D C, C E, and E D form an equilateral triangle, *i.e.*, they give a balanced three-phase supply. Further, if a point G is

obtained such that G C = G D = G E, that point can be used as the neutral. In order that this relationship may hold, the triangle C G D must be isosceles. $\therefore$ C D G = D C G = 30°

$$\therefore \text{G D F} = 30^\circ$$

$$\therefore \text{F G} = \text{D G} \sin 30 = \tfrac{1}{2}\,\text{C G} = \tfrac{1}{3}\,\text{F C}$$

i.e., number of turns between F and G $= \frac{1}{3} \times$ total turns on F C. Each primary has 50 turns per phase, and each is supplied at 6·6 kV, so that the voltage per turn in each unit is 6,600/500 = 13·2 volts.

Number of turns on D E $= \dfrac{500}{13 \cdot 2} = 38$

Since the voltage across F C $= 0 \cdot 866 \,.\, \text{D E}$

$\therefore$ Number of turns on F C $= 0 \cdot 866 \,.\, 38$

$= 33.$

Number of turns between F and G $= \dfrac{33}{3} = 11$, *i.e.*, neutral tapping.

Indicate the values of the currents flowing in the various branches of a star-connected auto-transformer transforming 5,000 kW at 0·8 p.f. from 6·6 kV to 11 kV. Neglect magnetising current and impedance drop in transformer (Fig. 311).

Current in 6·6 kV side $I_A = \dfrac{5{,}000 \,.\, 1{,}000}{\sqrt{3} \,.\, 6{,}600 \,.\, 0 \cdot 8}$

547 amps.

Current in 11 kV side $I_B = \dfrac{5{,}000 \,.\, 1{,}000}{\sqrt{3} \,.\, 11{,}000 \,.\, 0 \cdot 8}$

= 328 amps.

Current in star point $I_C = 547 - 328.$

= 219 amps. (approx.).

Two electric furnaces are supplied with single-phase current at 80 volts from a three-phase, 11-kV system, by means of two Scott-connected transformers with similar secondary windings. When the load on one furnace is 500 kW, and on the other 800 kW, what current will flow in each of the three-phase lines : (*a*) at unity power factor ; (*b*) at 0·5 power factor. Neglect phase displacement and efficiency of transformers.

Calling the 86·6 per cent. unit T_2, and the 100 per cent. (centre tapping) T_1, and allocating 500 kW to T_2 and 800 kW to T_1, for (*a*)

$$T_2 \text{ secondary current} = \frac{500 \,.\, 10^3}{80}$$

$$T_2 \text{ primary current} = \frac{500 \,.\, 10^3}{11{,}000 \,.\, 0{\cdot}866}$$

$$= 52{\cdot}5 \text{ amps.}$$

$$T_1 \text{ secondary current} = \frac{800 \,.\, 10^3}{80}$$

$$T_1 \text{ primary current} = \frac{800 \,.\, 10^3}{11{,}000}$$

$$= 72{\cdot}5 \text{ amps.}$$

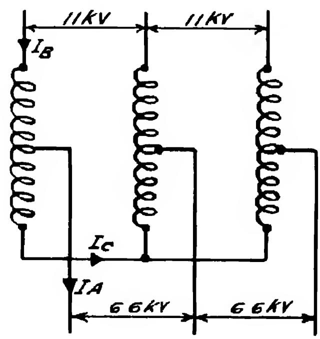


FIG. 311.

Current in line supplying T_2 is 52·5 amps., and on reaching the centre tapping of T_1 divides equally, each half flowing outwards from the tapping to the two supply lines. The current in these lines and in each half of T_1 consists of 72·5 amps., together with $\frac{52{\cdot}5}{2}$ amps. displaced 90°, the resultant being given by

$$\sqrt{72{\cdot}5^2 + 26{\cdot}25^2} = 77 \text{ amps.}$$

Therefore one three-phase line carries 52·5 amps., and the other two 77 amps. each. At 0·5 power factor, the currents are doubled.

Converting Plant. A choke coil of negligible resistance and reactance 0·05 ohm is inserted in each of the three lines connected to the slip-rings of a three-phase rotary convertor. If the supply

voltage is 350 volts, determine the voltage at the slip-rings when the machine is taking a current of 750 amps. at 0·87 p.f. leading.

(From Fig. 312)
$$\frac{V\cos\alpha}{E} = \cos\phi.$$

$$\therefore\ E.\cos\phi = V\cos\alpha$$
$$350\,.\,0{\cdot}87 = V\cos\alpha$$
$$\therefore\ V\cos\alpha = 304 \text{ volts.}$$
$$\text{Reactance drop} = \sqrt{3}\,IX$$
$$= \sqrt{3}\,.\,750\,.\,0{\cdot}05$$
$$= 65 \text{ volts.}$$

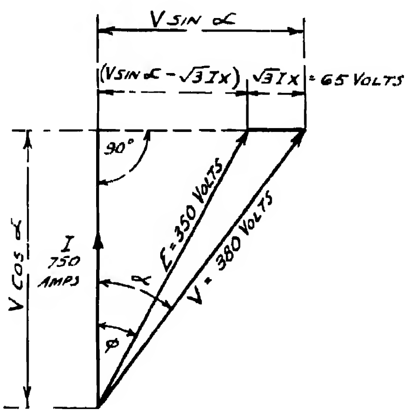


FIG. 312.

$$(V\sin\alpha - \sqrt{3}\,I\,X) = \sqrt{(E)^2 - (V\cos\alpha)^2}$$
$$= \sqrt{350^2 - 304^2}$$
$$= 170 \text{ volts.}$$

$$\text{Now } V = \sqrt{(V\cos\alpha)^2 + (V\sin\alpha)^2}$$
$$= \sqrt{304^2 + (170 + 65)^2}$$
$$= 380 \text{ volts approx.}$$

A six-ring synchronous convertor with diametral tappings is supplied from a 33 kV system, through a transformer star-connected on its primary side and having a turns ratio 44·5. Each phase has an

equivalent reactance of 0·2 ohm referred to the secondary winding. Find the change in commutator voltage due to a change in p.f. at the convertor slip-rings from unity to 0·8 leading. The D.C. load is constant at 500 amps., and a constant efficiency of 90 per cent.

Six-phase diametral tappings

$$\text{winding ratio} = \frac{E_L}{\sqrt{3}} \div \frac{E_{DC}}{\sqrt{2}}$$

$$44\cdot 5 = \frac{33{,}000}{\sqrt{3}} \cdot \frac{\sqrt{2}}{E_{DC}}$$

$$E_{DC} = \frac{33{,}000 \,.\, \sqrt{2}}{\sqrt{3} \,.\, 44\cdot 5} = 605 \text{ volts at 1 p.f.}$$

$$\text{Now } E_2 = \frac{33{,}000}{\sqrt{3}} \cdot \frac{1}{44\cdot 5} = 429 \text{ volts.}$$

Reactance drop per phase = current per phase × equivalent reactance.

$$\text{Load on D.C. side} = 500 \text{ amps.} \quad I_c$$

At unity p.f. and 90 per cent. efficiency

$$I_{AC} = \sqrt{2} \,.\, I_{DC}$$

$$= \frac{\sqrt{2} \,.\, 500}{0\cdot 9}$$

$$= 785 \text{ amps.}$$

$$\text{Current per phase} = \frac{785}{3} = 261 \text{ amps.}$$

$$\text{I X drop per phase} = 261 \,.\, 0\cdot 2$$

$$= 52\cdot 2 \text{ volts.}$$

$$\text{At unity p.f., } E_S^2 = E_2^2 - (I\,X)^2$$

$$= 429^2 - 52^2$$

$$E_S = 428 \text{ volts.}$$

$$\therefore \quad E_{DC} = \sqrt{2} \,.\, 428 = 605 \text{ volts at 1 p.f. as before.}$$

Considering the case of 0·8 p.f. leading and 90 per cent. efficiency. At a p.f. less than unity,

$$I_{AC} = \frac{\sqrt{2} \,.\, I_{DC}}{\cos\phi \,.\, e}$$

$$= \frac{\sqrt{2} \cdot 500}{0{\cdot}8 \cdot 0{\cdot}9} = 980 \text{ amps.}$$

$$\text{Current per phase} \quad = \frac{980}{3} = 326 \text{ amps.}$$

$$\text{Reactance drop per phase} \quad = 326 \cdot 0{\cdot}2$$
$$= 65{\cdot}2 \text{ volts.}$$

$E_2 = 429$ volts as before.

E_S can be determined graphically.

$= 465$ volts (Fig. 313).

$\therefore E_{DC} = \sqrt{2} \cdot 465$

$= 660$ volts at $0{\cdot}8$ p.f. leading.

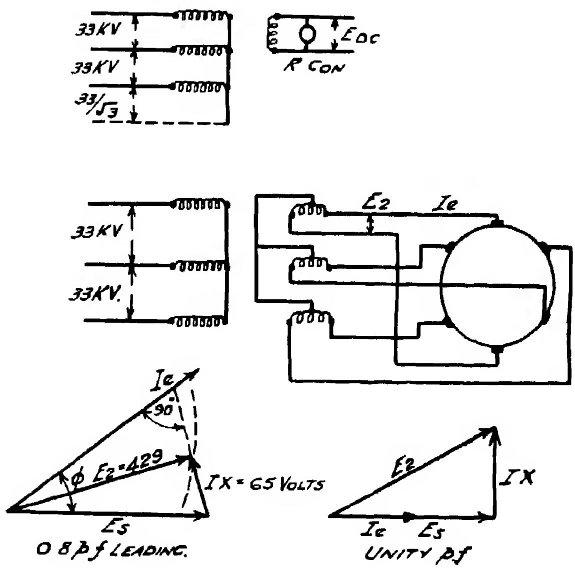


FIG. 313.

A sub-station supplies a load made up of 100 kW at 1 p.f., 400 kW at $0{\cdot}85$ p.f. lagging, and a rotary convertor having output of 500 kW at an efficiency of $0{\cdot}94$. Find the p.f. of the supply to the rotary convertor if the overall p.f. is to be unity.

$$\frac{400}{0{\cdot}85} = 470 \text{ kVA.} \qquad \begin{aligned} \cos\phi &= 0{\cdot}85 \\ \sin\phi &= 0{\cdot}527 \end{aligned}$$

Wattless lagging kVA $= 470 \,.\, 0{\cdot}527$
$= 248$

Rotary convertor, 500 kW at 0·94 per cent.

$$\frac{500}{0{\cdot}94} = 532 \text{ kW.}$$

Let x be p.f. of supply to rotary convertor so that overall p.f. may be unity :

$\therefore \dfrac{532}{x}$ will be kVA at x leading p.f.

$$\begin{aligned}\text{Wattless leading kVA} &= \frac{532}{x} \,.\, \sin \phi \\ &= \frac{532}{x} \,.\, \sqrt{1 - \cos^2 \phi} \\ &= \frac{532}{x} \,.\, \sqrt{1 - x^2}\end{aligned}$$

Wattless leading kVA = Wattless lagging kVA.

$$\begin{aligned}\therefore \qquad \frac{532}{x} \,.\, \sqrt{1 - x^2} &= 248 \\ \sqrt{1 - x^2} &= \frac{248}{532} \,.\, x \\ 1 - x^2 &= \left(\frac{248}{532}\right)^2 \,.\, x^2 \\ 1 &= \left[1 + \left(\frac{248}{532}\right)^2\right] \,.\, x^2 \\ x &= \sqrt{\frac{1}{1 + \left(\dfrac{248}{532}\right)^2}} \\ &= 0{\cdot}91 \text{ approx.}\end{aligned}$$

Switching of H.V. Transformers and Machines. The phenomenon associated with the switching in and out of high-voltage transformers and machines is of special interest to all associated with sub-station practice. Brief reference is made to this phenomenon in other sections of the work.

Switching In. Suppose I, Fig. 314 (*a*) represents the core of a transformer or machine, this core being earthed ; and 1, 2, 3, etc., represents the end turns of the high-voltage winding. Since the latter

is insulated from the core, a small condenser is formed by each turn and the core—as shown by *a*, *b*, *c*, etc. Immediately the circuit breaker is closed, turn 1 is brought up to line potential. The remainder of the winding is not instantly raised to the same potential. No turn can attain its full potential until the hypothetical condenser connected to it is charged ; and since this takes an appreciable interval of time—however short—potential is concentrated across the end turns during that period. Thus, before 2 can attain the potential of 1, *b* has to be charged ; similarly, *c* has to be charged before the potential of 3 can attain its full value ; and it is during this period of charging up the

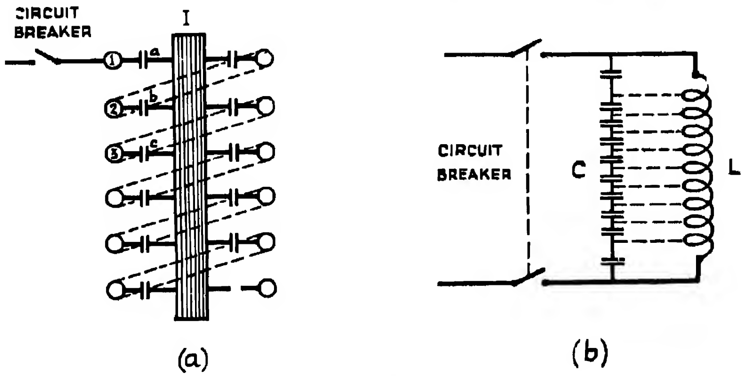


FIG. 314.

condensers formed between the various turns and earth that a large potential may exist between the adjacent end turns. Since some charging current flows into *c* and into those beyond it before *b* has been fully charged, it follows that the maximum difference of potential between two adjacent turns decreases as one gets farther from the first turn. It will be observed that the liability to failure from this cause occurs in the insulation between the end turns and not in that between these turns and earth. The risk of failure is minimised by arrangement of the insulation on the end turns (*see* Transformers) and another method is to connect a small external choke in series with each phase, the insulation between turns being arranged to withstand a relatively high voltage. Another phenomenon associated with switching in a transformer or a motor is the sudden rush of magnetising current which may take place. The magnitude of this transient current depends upon the value of the applied voltage at the instant of closing the

circuit breaker, being a maximum when the breaker is closed at the moment of zero voltage. This phenomenon, however, is not accompanied by any risk of breaking down the insulation.

Switching Out. Suppose a transformer or machine having an inductance L henries to be switched off, Fig. 314 (*b*). Let C farads represent a capacity equivalent to the distributed capacities between the various turns of the windings. If i be the instantaneous value of the current in L when the circuit breaker is opened, the electro-magnetic energy stored in L at that instant is $\frac{1}{2}$ Li^2 joules. If the resistance of the circuit and the energy lost in any sparking at the circuit breaker be neglected, all the energy stored in L will be transmitted to C, charging the latter to a potential e, such that—$\frac{1}{2}Ce^2 = \frac{1}{2}Li^2 \therefore e = i\sqrt{L/C}$. Hence, if either the current i or the ratio L/C, or both, are large, the voltage e across the insulation may reach a very high value. The most effective method of eliminating the risk of breakdown is to include an oil circuit breaker, since the latter breaks the circuit when the current is passing through its zero value and when the electromagnetic energy is consequently very small.

System Losses. The statistics relating to an undertaking give the units generated, units sent out, and units sold, from which the units lost or unaccounted for can readily be ascertained. The actual kW copper loss on the higher voltage systems may be calculated by using the maximum annual load figures, necessitating the maximum load on each feeder, and the respective resistances. The total loss at the time of the system maximum load may then be obtained. The annual loss in units depends on the annual load factor of the system, and the shape of the system load curve.

Total loss in units per annum $U_L = kW_{L.M.D.} \,.\, A\,L\,F_L \,.\, 8{,}760$

$kW_{L.M.D}$ = kW loss at time of maximum demand.

$A\,L\,F_L$ = Annual load factor of losses.

$$\text{Annual undertaking load factor} = \frac{\text{units sent out}}{\text{undertaking M.D.} \,.\, 8{,}760}$$

$$\text{Annual load factor of losses} = \frac{\text{units lost}}{\text{kW loss at U.M.D.} \,.\, 8{,}760}$$

The loss factor cannot be higher than the load factor, and the lowest value is approximately the square of the load factor. It is well nigh impossible to calculate the loss in the lower voltage networks. So far as transformer losses are concerned, the average copper loss may be taken as 1 per cent. at full load, and the iron loss as 0·7 per cent.

of the transformer capacity. Some attempt can be made to arrive at useful figures by reference to the undertaking daily load curve.

$$kW_{R.M.S.} = \sqrt{\frac{kW_1^2 + kW_2^2 + kW_3^2 + \ldots}{S}}$$

where S is the number of intervals between ordinates.

This result can be compared with the expression :

$$kW_{R.M.S.} = kW_{MD} \cdot \frac{\text{Daily load factor}}{100} \cdot K$$

where K is a constant the value of which depends on the load factor. In any of these calculations, assumptions must be made for power factor and voltage variation, etc.

Ventilation Data. The general requirements of a ventilating system may be estimated as follows :

A continuous loss of 1 kilowatt (1 kW) is equivalent to 3,412 B.T.U.s per hour, or 56·9 B.T.U.s per minute.

The specific heat of air is approximately 0·24 B.T.U. per pound, or 0·018 B.T.U. per ft.^{3}

Now heat lost = heat gained.

$\therefore$ 1 kW . 56·9 = 0·24 $(T_1 - T_0)$. W. per kilowatt loss, from which

$$W = \frac{kW \cdot 56{\cdot}9}{0{\cdot}24\,(T_1 - T_0)}$$

or

$$V = \frac{kW \cdot 56{\cdot}9}{0{\cdot}018 \cdot (T_1 - T_0)}$$

where W = weight of air in lb. per minute.
V = volume of air in ft.^{3} per minute.
kW = kilowatt loss to be removed.
T_1 = final temperature of air inside, °F.
T_0 = temperature of incoming air, °F.

The velocity of air through openings under natural ventilating conditions is comparatively low, and may be expressed by

$$v = \frac{Q}{A} = \sqrt{\frac{g \cdot (H_1 + H_2)}{1{\cdot}1}}$$

where v = final velocity leaving upper openings in ft. per second.
Q = volume of air, ft.^{3} per second.
A = area of openings in ft.^{2}
g = 32·2, acceleration due to gravity.

H_1 = head measured in feet of air column at temperature of outside air produced by the velocity of the wind perpendicular to the lower inlet openings in the side of the wall.

$$i.e.,\ H_1 = \frac{V_1^2}{2g}$$

where V_1 is the outside velocity measured perpendicular to the inlet openings.

If the effect of the wind is neglected, then $H_1 = 0$.

H_2 = head measured in feet of air column at temperature of outside air produced by the heating of the outside air.

The head due to the heated air is $H_2 = \dfrac{D\,(d_o - d_i)}{d_o}$

here D = vertical distance between lower and upper openings, ft.

d_o = density of outside air at temperature T_o.

d_i = „ „ inside „ „ „ T_1.

quantity of air discharged by the average efficient ventilator form (natural) is given by :

$$Q = A \,.\, \left[36 \,.\, \sqrt{\frac{H \,.\, (T_1 - T_o)}{6 + v}} + (20 \,.\, v)\right]$$

here Q = volume of air exhausted, ft.^{3} per hour.

A = free area of opening, ins.^{2}

H = height of ventilator above centre line of inlet, ft.

v = velocity of wind, miles per hour.

T_1 = average inside temperature, °F.

T_o = „ outside „ °F.

also Cu. ft. per minute $= \dfrac{1{,}830 \,.\, \text{kW}}{\text{Temperature rise } ^\circ\text{C.}}$

Speaking generally, such a ventilator may discharge as much as 30 per cent. more than the amount given by this formula, but it will be appreciated that a great deal will depend upon the location. A suggested minimum sectional area of inlet and outlet openings is 1 in.^{2} for every 10 ft.^{3} of chamber, whilst another rule is air inlet 12 ft.^{2} per 1,000 kVA, with air outlet 50 per cent. less. Another method of ascertaining the quantity of air required per kW of transformer loss, is :

$$Q = 27{\cdot}5\ \frac{(1 + \alpha \,.\, T_A)}{T_A - T_B}\ \text{ft.}^3/\text{sec.}$$

where a = coefficient of expansion of air $\frac{1}{273}$

T_A = temperature of air above transformer tank, °C.
T_B = " " " below " " °C.

Heating Data. To determine the amount of heat required for any particular building, it is necessary that the input should as nearly as possible be balanced against the losses which occur. The heat losses which take place are :

(1) Loss through walls, floors, and roofs due to the temperature difference which exists.
(2) Loss in each air change, which is brought about during the normal course of ventilation of the building.

There are numerous empirical formulae, and, so far as sub-sta are concerned, the following will serve as a guide to the appro such problems.

Heat required = weight of air × temperature difference × spe hea.

$$= W \,.\, (T_1 - T_o) \,.\, k_p$$

B.T.U.s per minute $= 0{\cdot}24 \,.\, W \,.\, (T_1 - T_o)$.

$$(T_1 - T_o = 32).$$

where W = lb. of air per minute.
T_1 = inside temperature of room.
T_2 = outside " " "

Expressing this in the form of kilowatts :

$$\text{B.T.U.s per minute} = \frac{\text{kW} \,.\, 1{,}000}{746} \cdot \frac{33{,}000}{778}$$

$$\therefore 0{\cdot}24\, W\, (T_1 - T_o) = \frac{\text{kW} \,.\, 1{,}000}{746} \cdot \frac{33{,}000}{778}$$

from which the heating capacity in kilowatts may be estimated. This fundamental calculation neglects any consideration or allowance for walls, floors, etc., and it is desirable that a factor of 1·5 to 2·5 be introduced.

Another method is :

$$\text{kW} = \frac{(30a + 8b + nC.) \,.\, 20{\cdot}4 \,.\, t}{36 \,.\, 10^5}$$

where a = window surface, ft.^{2}

b = wall ,, ,,

c = volume of building, ft.^{3}

n = air changes per hour.

t = temperature rise involved ($T_1 - T_0$).

A further method :

$$\text{kW} = \frac{A\,.\,K\,.\,t}{10^6}$$

where A = floor area, ft.^{2}

K = constant depending upon height of room.

t = difference of temperature (inside and outside) $T_1 - T_0$.

Building Calculations. Assumptions made in calculations are :

(1) Concrete carries no tensile stress.

(2) Concrete assumed to obey Hookes' Law, *i.e.*, stress α strain (very approximately).

(3) Reinforcement is assumed concentrated at some definite depth in the concrete, *i.e.*, stress in reinforcement is uniform.

Suppose neutral axis is at a distance h below compression edge of section (see Fig. 315).

Assume maximum compressive stress $= fc$.

,, ,, tensile stress in reinforcement $= ft$.

Strain at compression edge (concrete) $= \dfrac{fc}{Ec}$

Strain in reinforcement $= \dfrac{ft}{Es}$.

Where Ec and Es are the Young's modulus for concrete and steel, respectively.

By normal theory, the bending strain at section is proportional to distance of fibre from neutral axis (NA)

$$\therefore \quad \frac{fc/Ec}{h} = \frac{ft./Es}{(d-h)}$$

$$\frac{fc}{ft} = \frac{Ec}{Es} \cdot \frac{(d-h)}{h} \qquad \ldots\ldots\ldots\ldots \quad (1)$$

Because pure bending, net end load on section is zero.

Total compressive load $= \dfrac{b\,.\,h\,.\,fc}{2}$.

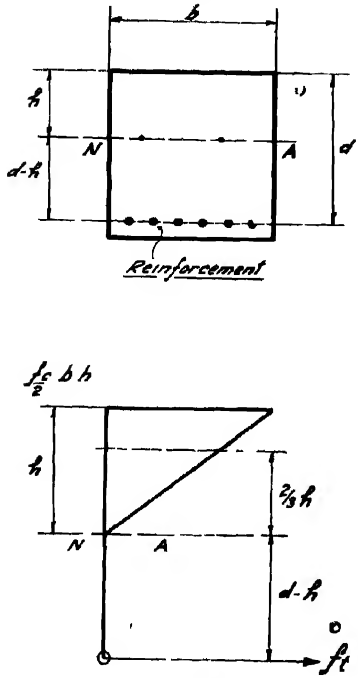


FIG. 315.

Mean stress $= \frac{fc}{2}$; (Area $A_c = b \cdot h$.)

Total tensile load $= ft \cdot A_S$

where A_S = area of steel reinforcement.
Since no net end load :

Compressive load in concrete = Tensile load in reinforcement.

$$\frac{fc}{2} \cdot b \cdot h = ft \cdot A_S$$

$$\frac{fc}{ft} = \frac{2A_S}{b \cdot h} \quad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

Solve for h and determine the position of the neutral axis (NA).
Moment of resistance of section = moment of compression ·load about NA + moment of tensile load about NA.

∴ Moment of resistance of section

$$\left(\left(\frac{fc}{2} \cdot b \cdot h\right) \cdot \frac{2}{3}h + (ft \cdot A_S)(d - h)\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The allowable compressive stress in concrete is assumed to be 600 p.s.i. (750–950 permissible).

The allowable tensile stress in steel reinforcement is assumed to be 20,000 p.s.i.

Young's Modulus for concrete is assumed to be $2 \cdot 10^6$ p.s.i.
,, ,, ,, steel ,, ,, ,, ,, $30 \cdot 10^6$,,

$$\text{Ratio } \frac{Es}{Ec} = \frac{30}{2} = 15$$

Substituting in equation (1) we have :

$$\frac{600}{20{,}000} = \frac{1}{15}\left(\frac{h}{d - h}\right)$$

$$\frac{3}{100} = \frac{h}{15\,d - 15\,h}$$

$$\therefore \qquad h = \frac{45}{145}\,d$$

$$= 0{\cdot}31\ d.$$

This result is verified graphically as shown in Fig. 316.

$$\text{The total compressive load} = b \cdot h \cdot \frac{fc}{2}$$

$$= \frac{b \cdot 0{\cdot}31\ d \cdot 600}{2}$$

$$= 93\ b \cdot d \cdot \text{lb.}$$

The total tensile load $= f_t \cdot A_S$.

Now area of steel as percentage of area of concrete

$$A = \frac{p \cdot b \cdot d}{100} \qquad \text{where } p = \text{per cent.}$$

$$\therefore \text{total tensile load} = 20{,}000 \cdot \frac{p \cdot b \cdot d}{100}$$

$$= 200\,p \cdot b \cdot d.$$

Compressive load in concrete = Tensile load in reinforcement.

$$p = \frac{93}{200} = 0{\cdot}465$$

Area of steel reinforcement (economical) $A_S = \dfrac{0{\cdot}465\, b \,.\, d \,.}{100}$ in.²

Moment of resistance of section $= \left[\left(\dfrac{fc}{2} . b . h .\right) . \tfrac{2}{3} h + (f_t . A_S)(d-h)\right]$

$$= \left[\left(\frac{600}{2} . b . 0{\cdot}31\, d\right) \tfrac{2}{3} . 0{\cdot}31\, h + (20{,}000 . A_S)\,(d - 0{\cdot}31d)\right]$$

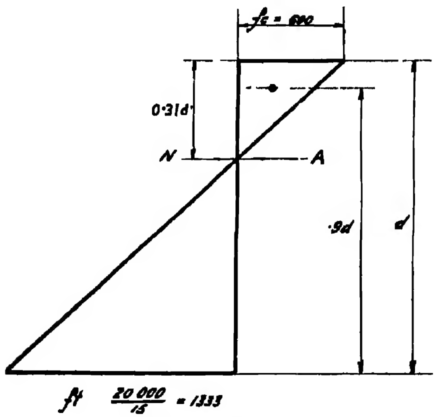


FIG. 316.

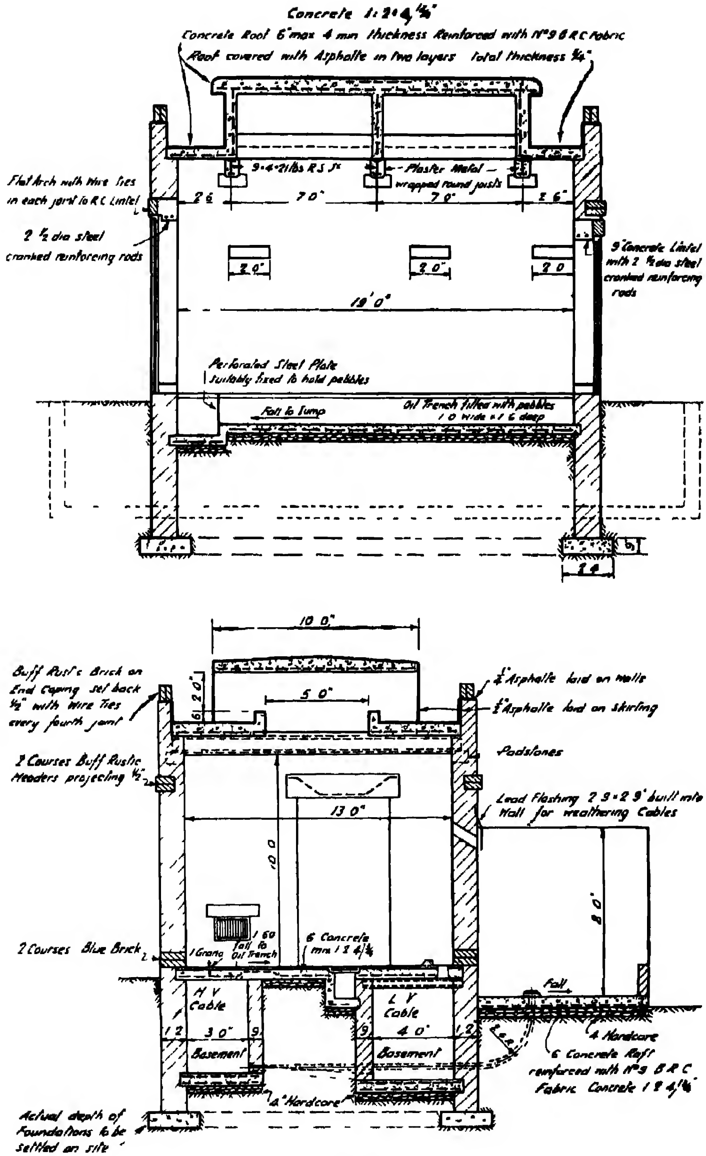
$$= (93\, b \,.\, d)\, 0{\cdot}206\, d + (20{,}000\, A_S)\,(0{\cdot}69\, d)$$
$$= 19\, b \,.\, d^2 + 13{,}800\, A_S \,.\, d.$$
$$= 19\, b \,.\, ^2 + 13{,}800 \,.\, \frac{0{\cdot}465 \,.\, d\, b}{100} \,.\, d.$$
$$= 83 \,.\, b \,.\, d^2 \text{ lb. in.}$$

As check M.R. of section $= 93\, b\, d \times 0{\cdot}9\, d.$
$= 83 \,.\, b \,.\, d^2$ (0·9 d from Fig. 316.)

Shear load in concrete $= 0{\cdot}9\, b \,.\, d \,.\, fs$

where fs is permissible shear stress in concrete = 60 p.s.i.

Considering building shown in Fig. 317.



Concrete 1:2:4, ¾"
Concrete Roof 6" max 4 min thickness Reinforced with No 9 B R C Fabric
Roof covered with Asphalte in two layers total thickness ¾"
Flat Arch with Wire ties in each joint to R C Lintel
2 ½ dia steel cranked reinforcing rods
9 × 4 × 21lbs R S Js
Plaster Metal — wrapped round joists
2 6
7 0"
7 0"
2 6"
9" Concrete Lintel with 2 ½ dia steel cranked reinforcing rods
2 0"
2 0"
2 0
19' 0"
Perforated Steel Plate suitably fixed to hold pebbles
Fall to Sump
Oil Trench filled with pebbles 1 0 wide × 1 6 deep
2 4
10 0"
Buff Rustic Brick on End Coping set back ½" with Wire Ties every fourth joint
2 Courses Buff Rustic Headers projecting ½"
2 0"
6
5 0"
¾" Asphalte laid on walls
¾" Asphalte laid on skirting
Padstones
Lead Flashing 2 9 × 2 9 built into Wall for weathering Cables
13 0"
10 0
8 0"
2 Courses Blue Brick
1 Grano
1 6 Fall to Oil Trench
6 Concrete min 1 2 4/¾
Fall
H V Cable
L V Cable
1 2
3 0"
9
9
4 0"
1 2
Basement
Basement
4" Hardcore
4 Hardcore
6 Concrete Raft reinforced with No 9 B R C Fabric Concrete 1 2 4/¾"
Actual depth of Foundations to be settled on site

FIG. 317.

Roof Loadings

Slab 6 in. thick maximum . .	75 lb.
Superimposed load	56 ,,
Snow	5 ,,
$\frac{3}{4}$-in. asphalt	6 ,,
	142 lb./ft.^{2}

Floor Loadings

Slab 6 in. thick	75 lb.
Superimposed load (150 M.V.A. switchgear)	225 ,,
	300 lb./ft.^{2}

Weights and Stresses

Concrete	150 lb./ft.^{3}	
Brickwork	120 ,,	
Steelwork	7·5 tons/in.^{2}	tensile.
Concrete	60 p.s.i.	shear.
,, ...	600 ,,	compression.
,, ...	20,000 ,,	tensile.

Roof Joists

Span 13·5 ft. (142 lb. × 7 ft.)

$$B\,M = \frac{WL}{8} = \frac{WL^2}{8} = \frac{142 \,.\, 13\cdot5 \,.\, 13\cdot5 \,.\, 12 \,.\, 7}{8 \,.\, 2{,}240}$$

$$= 121 \text{ tons ins.}$$

Now B.M. = M.R. Where Z = section modulus.

$$= Zf_t.$$

∴ 9 in. × 4 in. × 21 lb. R.S.J. — Z = 18·03.

Floor Joists

Same method.

Floor Slab

Worst case, 4 ft. 9 in. span.

Load per sup. ft., 300 lb.

Effective depth = 7 in. — $\frac{3}{4}$ in. ($\frac{3}{4}$ in. reinforcement cover.)

= $6\frac{1}{4}$ in. 1 in. grano finish.

(300 lb. × 4·75 ft.)

$$B\,M = \frac{WL}{8} = \frac{4\cdot75 \,.\, 300 \times 57}{8}$$

$$= 10{,}000 \text{ lb. in.}$$

$$\begin{aligned} \text{M.R.} &= 83\, b\, d^2 \\ &= 83 \,.\, 12 \,.\, 6 \cdot 25 \,.\, 6 \cdot 25 \\ &= 39{,}000 \text{ lb.-in. per ft. of width.} \end{aligned}$$

$$\begin{aligned} A_S &= \frac{0 \cdot 465\, b\, d}{100} = \frac{0 \cdot 465 \,.\, 12 \,.\, 6 \cdot 25}{100} \\ &= 0 \cdot 35 \text{ in.}^2 \text{ per ft. width (economical)} \end{aligned}$$

or

$$\begin{aligned} A_S &= \frac{\text{B M}}{0 \cdot 9\, d \,.\, f_t} \\ &= \frac{10{,}000}{0 \cdot 9 \,.\, 6 \cdot 25 \,.\, 20{,}000} \\ &= 0 \cdot 090 \text{ in.}^2 \text{ per ft. width.} \end{aligned}$$

Using No. 9 B.R.C. fabric, area $= 0 \cdot 142$ in.^{2}/ft. width and nearest size would do.

$$\text{Maximum shear} = \frac{4 \cdot 75 \,.\, 300}{2} = 710 \text{ lb.}$$

$$\begin{aligned} \text{Permissible shear in concrete } &= 0 \cdot 9^2 \,.\, b \,.\, d \,.\, fs \\ &= 0 \cdot 9 \,.\, 12 \,.\, 6 \cdot 25 \,.\, 60 \\ &= 4{,}050 \text{ lb.} \end{aligned}$$

Roof Slab

Same method.

Beam Tension Strips

Width of tension strip $= 0 \cdot 4$. length of span.

Transformer Slab

Transformers usually have either skids or wheels. 500 kVA transformer, about $5\frac{1}{2}$ tons. With four wheels, say, $1\frac{1}{2}$ tons/wheel. Reinforcing steel will assist to spread this load over a reasonable area, and in practice it appears that a 6 in. thick slab with No. 9 B.R.C. fabric is suitable.

Ground Loading (side walls)

Load per lin. ft.	lb.
Roof	500
Wall	2,600
Floor slab	900
Foundation	260
	4,260

$$\therefore \text{Load per ft.}^2 = \frac{4{,}260}{2\cdot 33 \,.\, 2{,}240}$$
$$= 0\cdot 82 \text{ tons.}$$

End walls can be dealt with in same manner.

Whilst it is realised that this information only gives the fundamentals, it affords a method of approach by the electrical engineer when initiating such projects.

Bibliography

R. J. Birkenshaw. "Transmission Line Surges," *Electrical Review*, 6th July, 1945.

D. J. Bolton. "Electrical Engineering Economics." (Chapman & Hall.)

T. H. Carr. "Electrical Calculations for Students," *The Electrician*, 1934.

——. "Power Factor Improvement," *Mechanical World*, 7th December, 1945.

C.B.Y. "Voltage Distribution Across Insulators," *Distribution of Electricity*, March, 1951.

C. L. Fortescue. "Condenser Type Outlet Terminal," *The Electric Journal*, Vol. 10, 1913.

C. L. Fortescue and S. W. Farnsworth. "Air as an Insulator when in the presence of Insulating Bodies on Higher Specific Inductive Capacity," *Journal A.I.E.E.*, Vol. 32, 1913.

Sir Frank Gill. "Engineering Economics," *J.I.E.E.*, 1943.

B. L. Goodlet. "The Design of Condenser Type Bushing Insulators," *World Power*, Vol. 28, January, 1935.

J. W. McQuillen. "Insulating Oil," *Electrical Times*, 15th December, 1949.

G. S. Monk. "Classical Examples in Electrical Engineering." (Pitman.) (Vol. 2.)

G. W. Stubbings. "Elements of Symmetrical Component Theory." (Pitman.)

W. Wilson. "The Calculation and Design of Electrical Apparatus." (Chapman & Hall.)

E. G. Wright. "Bushing Insulators," *Electrical Review*, 10th May, 1946.

CHAPTER X

ORGANISATION AND CONTROL

Sub-station Organisation. It will be appreciated that it is difficult to lay down any hard and fast rules for the organisation of a sub-station's department which will apply to all authorities.

In a very large supply authority the work is so varied in character that it is impossible to cover the distribution engineer's work by a mains' superintendent alone, and it is inevitable that a sub-station's engineer will be required to give particular attention to rotary and converting sub-stations. The sub-division of sub-stations into three classes may be justifiable on very large undertakings, and one authority has adopted the following :

(1) Manually-operated sub-stations.

(2) Consumers' sub-stations.

(3) Automatic, rectifier and static sub-stations.

The accompanying organisation diagrams (Figs. 318–320) show

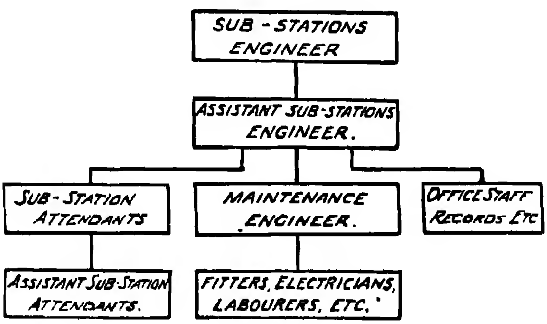


FIG. 318.

various grades of staff required in a sub-station's department and the titles are generally self-explanatory. As far as the shift men, or sub-station attendants are concerned, their duties generally comprise the following :

Maintenance of supply ; machine operation and the economical running of machines in accordance with the demand ; care and charging of batteries ; logging of the load and happenings ;

routine electrical testing, including traction leakage test ; testing alarm circuits.

If assistant attendants are employed they will, in addition to assisting in these duties, attend to all recording instruments—inking

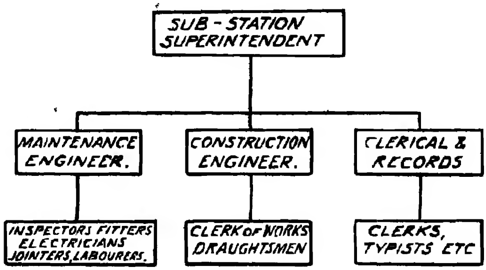


FIG. 319.

pens, changing and labelling charts, cleaning switchboards, machines, rectifiers, and transformers ; and attend to commutators and the bedding of brushes.

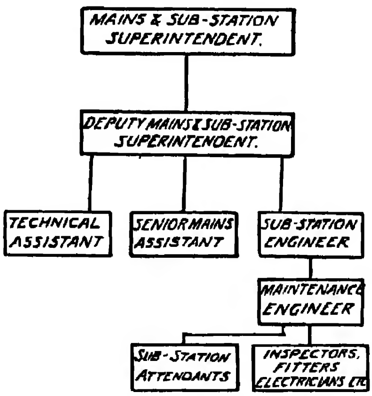


FIG. 320.

The reporting of breakdowns, and failure of supply from any sub-station, is the duty of the attendant, who immediately gets into touch with the system control engineer by telephone.

Arrangements are also made with the staff to cater for attention to emergency calls, and it is usual to draw up a schedule, or rota, for

dealing with such eventualities in turn, *e.g.*, first, second, and third call.

In the past a sub-station attendant's job has sometimes been regarded as a dead-end one, but if young engineers have qualified technically and practically before taking such a post, it is generally a good step towards further progress. That this is so can be borne out by the fact that many eminent supply engineers at one time occupied such posts. I would suggest that, if possible, no more than two years should be served in this position ; much, however, will depend on the possibilities of promotion and the individual.

System Control. The transmission, transformation, conversion and distribution of electrical energy over large and complicated systems have rendered necessary the provision of a control centre to co-ordinate operation so that safety and efficiency are ensured. In the early days it was assumed that, in normal conditions and with sound protective schemes, whenever a circuit breaker opened automatically it did so in order to isolate a faulty circuit. If the opening of the circuit breaker did not affect the supply, it was usually not discovered until the next routine inspection.

With the ever-increasing importance of electric power supply, a central control room is necessary for large interconnected systems to deal promptly with the many problems associated with such systems. The principal objects of centralised control are safety of operating personnel and continuity of supply. The organisation should be such that the control engineers are immediately informed of any abnormal operating condition, and they should be thoroughly conversant with the rated capacity of the plant available, and the stand-by, at each power station and sub-station ; the exact loading conditions of the system ; the network demands ; the rating and loading of all plant, including lines and inter-busbar transformers, and the types of protection in use. The control engineers should also maintain close contact with all happenings on the system, especially where men are working on higher voltage apparatus. The advent of the Grid system, with the subsequent division of the country into areas, brought into service a more elaborate type of control centre for each area, which deals primarily with load distribution in bulk as circumstances demand for each authorised undertaking connected to the Grid in that particular area. Load transfer to or from other areas is also effected from these control centres. Speed variations are carried out by way of the chief control engineer, and the sub-station attendants advise those concerned

and synchronise any interconnecters which may be connected to the sub-stations under their control.

The more usual type of control centre is that used by supply undertakings having their own large interconnected systems, where the control engineers are in complete charge of the system. The functions of system control may be outlined as follows :

(1) Safe and efficient operation of the system and subsidiary networks.

(2) Restoration of supplies.

(3) Maintenance of supplies under both normal and abnormal conditions.

(4) Supervision of switching operations.

(5) To co-operate with consumers and arrange to meet their requirements in respect of interruptions, etc.

(6) Routine record and office work.

To transmit and distribute electric power over large areas, power stations and major sub-stations are interconnected by cables and overhead lines, thus obtaining a reliable and efficient system. Local lower-voltage networks may be supplied from the main distribution centres and from power stations at voltages down to 6,600 volts. At the sub-stations connected to these networks, step-down transformers are used, and the voltages given at the consumers' terminals vary from 3,000 volts for industrial supplies down to 240 volts for the domestic consumer.

The economical and reliable functioning of such a system involves many technical problems, for apart from normal and abnormal running conditions, maintenance, operation and extension, all have to be given careful consideration.

Some of the factors which have to be considered almost on a day-to-day basis are :

(*a*) Load distribution ;
(*b*) Voltage distribution ;
(*c*) Short circuit M.V.A. ;
(*d*) System losses.

The first essential, in so far as load distribution is concerned, is that the consumer(s) must under all system conditions receive a reliable supply. The previous years' maximum demands will give some idea as to the rate of growth, Fig. 321, whilst the possibility of immediate new loads in the areas affected must all be reviewed, so that due pro-

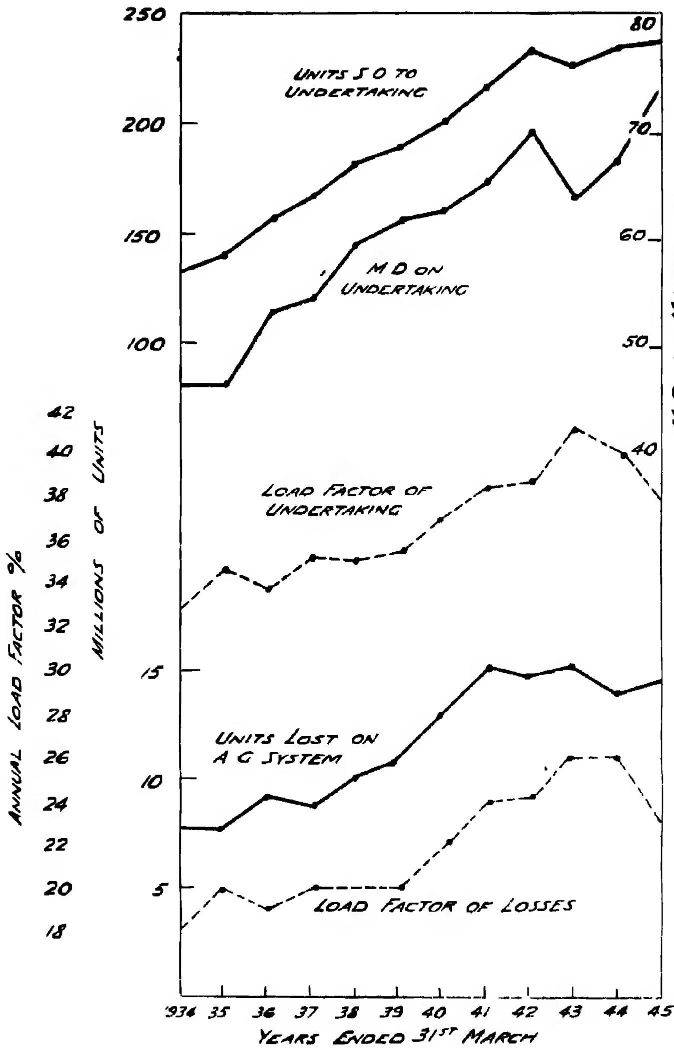


FIG. 321. System data.

vision may be made for the ordering of new equipment and possible alterations to existing networks. Here, again, the financial aspect

commands respect, and it is usual to consider alternative schemes before an economic and practicable solution is found.

Voltage calculations naturally follow load distribution, and are important, since certain statutory obligations have to be met in respect of consumers' terminal voltage. The Electricity Commissioners' Regulations of 1937—Regulation 34—in this connection specify the following :

(*b*) " . . . and the voltage declared as aforesaid shall be constantly maintained subject as respect the frequency to a permissible variation not exceeding 1 per cent. above or below the declared frequency and as respects the voltage to a permissible variation not exceeding 6 per cent. above or below the declared voltage. . . ."

" Provided that any supply of energy at high voltage for the time being given by the undertakers in accordance with a requirement of any prior regulations that the energy should be supplied at a voltage not less than a declared minimum at the supply terminals and not exceeding the said minimum by more than 12½ per cent. shall unless otherwise agreed between the undertakers and the consumer be continued by the undertakers in accordance with that requirement unless the Electricity Commissioners otherwise allow in manner provided for in this regulation."

Where networks give supply to furnaces, rolling mills, colliery winders, etc., which usually impose heavy and repeated " kick " loads, trouble may be experienced due to " flick " voltage variation.

The correct determination of the short circuit or fault M.V.A. on a large interconnected electrical system is rather difficult, and some degree of safety factor should of necessity always be allowed. Methods of estimating network fault M.V.A. are dealt with in Chapter IX.

Fault calculations are, of course, required in connection with the protective gear relay settings, so that correct fault discrimination is obtained.

The fact that loss calculations are rarely mentioned does not imply that they can be ignored, for a system loss of from 5 to 10 per cent., Figs. 322 and 323, is by no means uncommon, and on very large systems this means an appreciable financial loss to the undertaking. Some losses are inevitable, but, unless due care is taken, a considerable proportion may be wasted by inefficient distribution. To enable these factors to be adequately dealt with, the data necessary includes :

Size, length, resistance, reactance and impedance of the higher voltage cables and overhead lines.

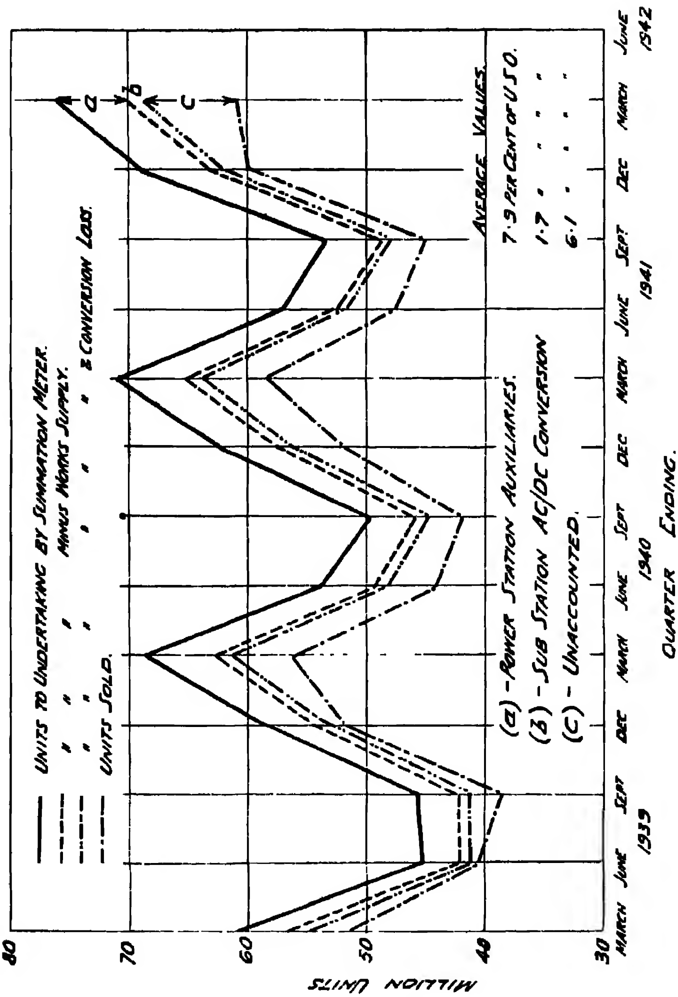


Fig. 322. Undertaking unit loss.

Size, voltage ratios, resistance, reactance and percentage impedance of transformers.

Ratings and percentage reactance of generating plant, synchronous plant and reactors.

Ratings and particulars of tappings on all " on-load " tap changing transformers, regulators, boosters, etc.

Sub-station and distribution network maximum demands. System and sub-station diagrams of main connections.

Where the growth of load is rapid a great deal of work will be entailed in maintaining this information up to date, and careful attention to detail is necessary.

Control Centre Organisation. The administration is built up around the existing mains or distribution department's organisation, or, alternatively, under what is known as the operation department.

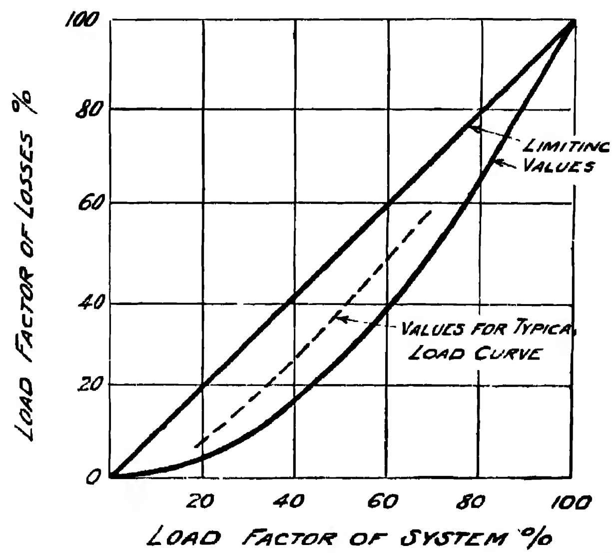


FIG. 323. Effect of form factor of load curve on load factor of losses.

The policy relating to control of transmission and distribution is predetermined as far as the normal routine work is concerned, it being well-nigh impossible to legislate for all happenings. A shift control engineer is on duty, with, perhaps, the assistance of a junior engineer to deal with telephone calls, load readings, reports and routine switching operations. Isolation of feeders and distributors for testing purposes, preparation of switching schedules, calculation of protective gear settings for new or altered operating conditions, are also included in the work carried out under the supervision of the system control engineer. The system control engineer and his principal shift control

engineers should have an intimate knowledge of the entire system, including all power stations and primary interconnecting sub-stations, and, in addition, should be familiar with the construction and operation of the many types of switchgear, transformers, converting and rectifier plant and all ancillary apparatus.

Modern networks are usually so trouble-free that the engineers have little opportunity of becoming familiar with many practical details which, in emergency, all tend towards reducing an outage period to a minimum.

On large systems, a number of the sub-stations may be manned, also certain of the main switching stations are staffed as required for ensuring efficient operation of the system. These attendants have certain standing instructions for the operation of the system, as, for instance, the operation of the network circuit breakers in the event of a trip-out, and they always maintain contact with the shift control engineer. Should an interruption occur on a feeder supplied from an unattended sub-station, the department's office may be notified, and an attendant or engineer is detailed to carry out switching operations to the shift control engineer's instructions. A rota for " out of office hours " duty may be adopted, thus facilitating matters in an emergency.

On very large systems, it is usual to sub-divide these into areas or districts and appoint a district mains' engineer, who is kept informed of any faults in his particular area and the degree of sectionalising carried out.

Staffing and Routine. Hard and fast rules cannot be laid down, and it is always necessary to review present conditions and possible ultimate requirements before formulating any scheme of system control and organisation.

It is customary for the mains' superintendent or distribution engineer to have charge of the system control centre, which maintains a continuous record of the system, in addition to the staff carrying out switching operations and the general routine records associated therewith. The larger authorities are often organised to include an operation department, the head of which is responsible for all matters relating to system control operation. The staff of a control room for such a system will normally comprise:

A chief or senior control engineer.
Control engineers (shift duties).
Junior engineers (ditto).

Maintenance staff for supervisory equipment.

Draughtsmen—system, sub-station, and control diagrams, etc.

Technical clerks.

Typists.

The deputy chief operation engineer or the senior control engineer deals with all matters appertaining to the control centre staff and organisation. He makes all recommendations concerning control room equipment and metering and supervisory equipments, attends operation and distribution co-ordinating meetings, thereby maintaining close contact with all system developments.

In some undertakings a chief control engineer is appointed, and in such cases the senior control engineer acts in a supervisory capacity over the control staff generally. He formulates operational programmes, and collaborates with the operation and construction departments to arrange for maintenance and construction on the system. The checking and issuing of load curves, load readings, fault reports and special reports relating to system loading, together with pressure testing, phasing and tap connections, all come under his care.

The shift staff required will depend upon the size and extent of the system under control, and for a large undertaking it may include one control engineer, two assistant control engineers, one junior engineer, and one typist, per shift. The shift control engineer is in sole charge, and deals generally with load distribution and regulation on the system. The assistant engineers each take care of one part of the system, while the junior undertakes the usual routine work concerning readings, logging, making load curves, and taking checks on the supervisory equipment. All switching operations and other information are recorded in the control log book for each shift. From this, station running hours, outage periods, area affected, etc., are taken and reports compiled. System loadings and feeder readings are reported and entered, and daily load curves drawn. Manned sub-stations submit weekly reports and loadings. The weekly load readings give some idea of the maximum conditions to be allowed for in the event of having to isolate any sections.

The control engineer decides the most convenient period when it is safe to sectionalise and supply on, say, one leg, keeping in mind the need for a stand-by supply if special consumers are served from the feeders concerned. When outage period is agreed, notices are sent to the consumers affected. A switching schedule is issued outlining the work to be undertaken : section(s) to be made dead, period

covered, and anticipated duration of outage, copies of this schedule being sent to the district engineer and any sub-station engineers concerned. All interim operations are reported and entered in the shift control log book, and the system diagram is altered in step with operations from the placing of danger labels to the final positioning of indicators for which provision is made.

The control engineer decides what generating plant and converting plant will be required to be run, according to a programme arranged weekly in conjunction with the operation department. Stand-by power station plant is decided on to meet system conditions, as large additional demands may have to be met at very short notice due to local or weather conditions, etc., whilst allowance has to be made for the possibility of failure of certain sections of generating plant. In so far as holidays, weather, and other conditions are concerned, past load curves are useful as a guide.

The control engineer is responsible for all high-voltage switching, and his permission must be obtained before any such operations are carried out. All high-voltage switching is very carefully considered, and always follows a proper routine. They are recorded on the control diagram as well as logged in precisely the order of carrying out. When any high-voltage apparatus, feeder, distributor or transmission line has to be made " dead " for repairs or maintenance, a " Permit to Work " card is issued by the authorised engineer in charge of the work. This declares that the apparatus is " dead " and all live parts guarded according to the control engineer's instructions. When the " Permit to Work " card has to be cancelled by the authorised engineer issuing the card, the control engineer, after satisfying himself that everything is in order, will give the instructions for making the equipment alive, and, after this has been done, the control diagram will be altered accordingly. Any failure of supply or disturbance on the system is immediately reported to the control engineer, and he is solely responsible for issuing instructions as to the procedure to be adopted, and resuming supply as soon as possible.

High-voltage equipment which has failed in service and is not immediately required for operation purposes is usually handed over to the operation staff for repairs. Before such equipment is put back into service the control engineer must ascertain and log particulars relating to the failure and the repairs carried out, and must also see to it that all tests have been made.

When an interruption occurs it is usual to issue a fault report

notice to all departments concerned. These reports are analysed and recorded by the section concerned, and the necessary steps are taken to prevent a recurrence of similar faults. The control engineer is responsible for the load distribution, voltage, and, maybe, frequency regulation on the entire system. The load conditions have to be kept under observation, particularly in so far as the demand on the power stations and loading of important feeders are concerned.

Voltage regulation is very important, and the voltage is generally regulated according to readings from key points on the system. Recording voltmeters may be installed at key points on the system, thereby giving a true record of conditions obtaining on the networks. With alternators or transformers operating in parallel, the voltage of one may be raised, thereby increasing its current loading. Interconnectors should not be overloaded with circulating wattless (reactive) current, for this may lead to instability. The wattful (kilowatt) loading is adjusted by operation of the turbine governors, and coupled with this is the regulation of frequency. In practice, it is usual for one station—generally the largest—to be given a definite base load, and others instructed to pick up or drop load to maintain standard frequency. Should all stations attempt to pick up load simultaneously, the frequency will rise, or *vice versa.*

Under normal system operating conditions, it may be necessary to have certain circuits left open to limit the fault M.V.A. according to circuit breaker rupturing capacity. Such circuits can be closed in an emergency, and it is possible to provide remote control equipment, so that operation is effected from the control centre.

It is impossible to give a detailed description of the work carried out by the control-centre staff, nevertheless, it is of high importance, and a sound knowledge of the system and its equipment is necessary. A control engineer is responsible for the following during his shift :—

(1) All switching.

(2) Regulation of voltage, frequency and power factor, and maintenance of continuity of supply.

(3) The transmission and distribution of electrical load on each point on the system and between different power stations.

(4) The number of machines on load, available and stand-by, at each power station and sub-station, and the allocation of load on individual machines so as to obtain maximum operating efficiency.

(5) Keeping record of all switching, linking and earthing carried out, with the times of the operations, and the names of the operators.

(6) Recording of hourly loadings at each station and on important feeders.

(7) Recording weather conditions and taking routine precautions necessary to safeguard supplies.

Other duties may be added, which vary according to circumstances and local conditions.

Location of Control Centre. Regarding the position of the control centre, much will depend on the extent and physical disposition of the electrical system, but if possible it should be located near the physical centre of the system. It may be at a power station, a primary sub-station, or at the head offices. On many of the larger authorities the last-named has been favoured. For an undertaking having one power station it would appear that there are advantages in having the control centre in the power station control room, particularly if the station is in a convenient position in relation to the system. During the war, the control centre proved very useful for co-ordinating the local A.R.P. services in relation to electricity supply, special emergency control officers being on duty for this additional work. Here again the location of the centre often played a considerable part in the receipt and transmission of emergency messages.

Control Room Equipment. The equipment and apparatus required for complete centralised control of a large interconnected system may be summarised as follows :

(1) System control diagram.
(2) Communication systems.
(3) Metering equipment.
(4) Supervisory control equipment.

System Control Diagram. The diagram provides a complete picture of the electrical system, and the form which it takes depends to a large extent on the opinions of the engineers responsible for its design, but is generally of the wall type. A very complete system of control, including many of the higher voltage circuit breakers and equipment is provided. The majority of diagrams show the higher voltage systems, together with circuit breakers, transformers, converting plant, and the routes of control cables. Use has also been made of distinctive colours for each voltage, lower voltage networks and consumers' connections being omitted. Very large diagrams requiring more than one control engineer on duty per shift, are wall-mounted and of circular form. The object in the design of such

electrical diagrams should be to obtain simplicity, avoid cross-overs, and arrange power stations and sub-stations as geographically correct as is practicable. The colour scheme of the diagram is of considerable practical value ; the markings on the discs may convey useful information, *e.g.*, red disc a circuit breaker closed, and a green one that it is open. If the red disc bears a small white centre, it denotes circuit breaker closed on overcurrent protection, the actual relay setting being recorded on another white disc near by. Different discs can be used for other forms of protection.

In the earlier days of electric power supply, when systems were comparatively small, coloured lines on a white background usually sufficed. There are numerous alternatives, some of which are : phosphor bronze strips and stampings pinned on a special plywood board ; wires and press-stud buttons for circuit breakers ; electrically-operated telephone type keyboard ; magnetised board, the symbols being held in position. A diagram can have the lines, transformers and circuit breakers, etc., illuminated. Fig. 324 illustrates one type of diagram.

Fig. 325 indicates a system phase diagram. The transformers are normally connected externally, that is, in such a manner that corresponding phases, as determined by BSS171, bear the phase relationship indicated by the vector group reference, *e.g.*, 42Yd3 indicates that the lower voltage vectors lag 90° behind the corresponding higher voltage vectors. The terminal colourings have been selected accordingly ; *i.e.*, in this example the red phase on the lower voltage lags behind the red phase on the higher voltage side by 90°, where, because of existing connections, it has been necessary to diverge from the above arrangement this is specially noted on the diagrams by an asterisk.* The phase rotation is in all cases, red-white-blue-red-white.

Telephone Equipment. Some authorities have one or more secret (ex-directory) telephone numbers, to afford ready communication with operating engineers and control room. These are useful during emergencies, having proved of especial value when air raids were dislocating supply systems.

Others have a private system, using lines rented from the G.P.O., or special pilot cables laid when power cables are being installed. An efficient telephone system is complementary to the control system diagram, and is usually justified on all systems where rapid growth of load is inevitable. Telephone pilots are now used for remote metering and supervisory control.

Some of the larger authorities have private telephone systems which are connected to all primary and district sub-stations. Telephone equipment may be in duplicate to permit either of two control engineers to operate any selected portion of the system. To ensure continuous communication, avoid delays and facilitate operation, a ring line to each sub-station in each district and connected to the control room is necessary.

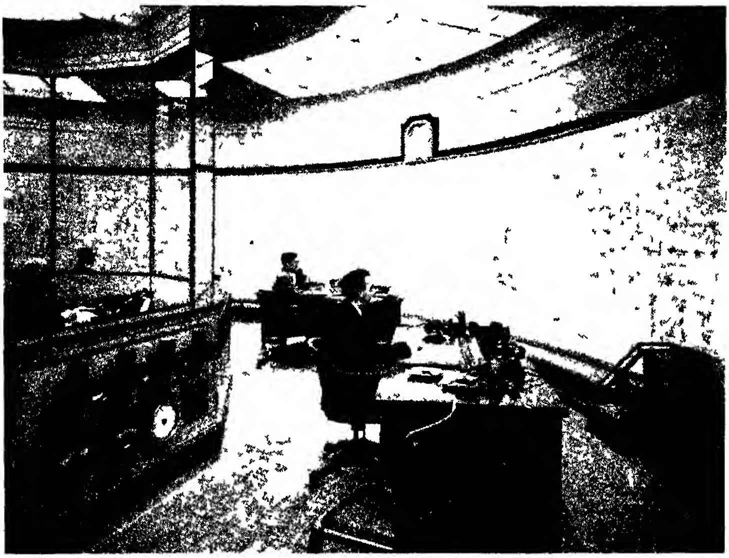


FIG 324. System control room.

Metering Equipment. Indicating and recording instruments enable the control engineer to note kW load on each power station and primary sub-station, together with the essential system voltages. The recording instruments give a continuous graph of transmission voltages and system frequency. Summation wattmeters and voltage indicators are useful under all operating conditions, whilst the frequency indicators are indispensable when stations have lost synchronism due to system troubles. One pair of pilot or telephone wires is used for each indication, although it is possible to give up to eighteen continuous meter readings simultaneously over one pair of wires. Miniature instruments allow them to be grouped and mounted on a reasonable size of control panel.

The growth of power distribution systems, and the use of automatic sub-stations, have encouraged the development of supervisory systems which provide a combination of telemetering and remote-control facilities. There is, however, scope for a simpler system which superimposes telemetering functions on a normal telephone circuit and allows distant operations to be manually effected by local staff. An ideal telemetering system for certain applications is one which requires only a single telephone circuit between remote station and control centre ; provides facilities for the transmission of a large number of meter-readings and/or " condition " signals ; operates on a simple principle ; is unaffected by the simultaneous use of the same circuit for speech or audio-frequency signal transmission ; is unaffected by other circuit characteristics, or by battery voltage variation and uses a minimum of equipment. Remote indication by a self-balancing Wheatstone Bridge signalling system has been developed to meet these requirements.

Supervisory Control Equipment. Telephone type equipment is employed for indication and metering purposes, also for remote control of apparatus from the control centre. The equipment installed enables the following indications and operations to be carried out :

Circuit breaker indication—Open and closed.

Feeder and transformer loads—Amperes, kilowatts, reactive kVA, power factor.

Tap change indication and alarms—From " on load " tap change transformers and regulators.

Protection indication—In connection with feeders controlled (closing and tripping) from the control centre.

Remote control of circuit breakers—Closing and tripping.

Remote control of transformers and regulator tappings.

Remote control of transformers—Parallel, automatic and non-automatic operation.

Remote control of voltage relays for automatic " on load " tap change transformers.

These indications and operations can be carried out over one pair of telephone wires between the control centre and the distant station. The equipment consists of relays and rotary switches used in automatic telephony, the operating current being taken from 50-volt batteries. Indications and operations function on a code system of impulses over a pair of wires between the sub-station and control centre. For circuit breaker indications, auxiliary contacts on the breakers are connected to relays or condensers, and change of position starts a selector or sender

apparatus, and the code of impulses associated with the breaker affected is sent to the control centre. Here certain relays respond to the code received and complete lamp and alarm circuits. Tap change and protection indications are given in a similar manner.

A special instrument is installed at each sub-station if meter readings are desired. This instrument may be connected continuously in the circuit to be metered, or a common instrument may be used which is automatically transferred from one circuit to another when readings are required. This is a form of contact metering, and may be used on all types of measuring instruments, but as the indications are spot readings they are not used for indicating important loads with large continual fluctuations. Remote operation from the control centre is also carried out on the impulse system.

All indications and positions can be checked from the control centre by operating check keys. Check systems are provided in the circuits to obviate the possibility of incorrect indication or selection. Where outlying sub-stations supply important tail-end feeders which serve a number of networks, then equipment can be installed to give protection indication in addition to circuit breaker indication in the control centre. The circuit breakers can also be closed or tripped, and should one of the feeder circuit breakers trip, this is indicated together with the protection relay affected. If the breaker has tripped due to an earth fault, then the control engineer may close the breaker from the control centre, and if it remains closed (overhead line fault usually clears), then a saving is effected—both in money and goodwill.

OPERATIONAL NOTES

GENERAL INSTRUCTIONS TO SUB-STATION ASSISTANT ENGINEERS

Unauthorised Entry to Sub-station. No unauthorised person is to be admitted to any sub-station.

Switching. The H.V. circuit breakers controlling feeders, transformers, and busbar section switches are only to be operated on instructions from the system control engineer.

On metal-clad H.V. switchgear no circuit breaker is to be racked out except on instructions from the system control engineer. On

racking out any circuit breaker the orifice covers must be locked closed *immediately*.

On cubicle H.V. switchgear the doors are not to be opened nor any cover removed by the attendant, and the isolating switches or links are not to be operated by the attendant.

All switching operations on H.V., M.V., or traction supplies are to be reported to the system control engineer. All switching must be recorded in the switching log book.

Interruption to Supply. All cases of irregularity in supply are to be reported immediately to the system control engineer. In the event of interruption to supply, act according to special instruction sheet referring to this matter. Before reclosing any circuit breaker reset relays and replace blown time limit fuses, unless instructions to the contrary regarding fuses are given by the system control engineer.

Interruptions to supply may fall under the following headings, and, in each case, the appropriate procedure should be adhered to except by special instruction from the system control engineer :

(1) Total shut-down due to failure of H.V. supply from power station (no feeders tripping at sub-station).

(2) Shut-down, including tripping of H.V. feeders in sub-station.

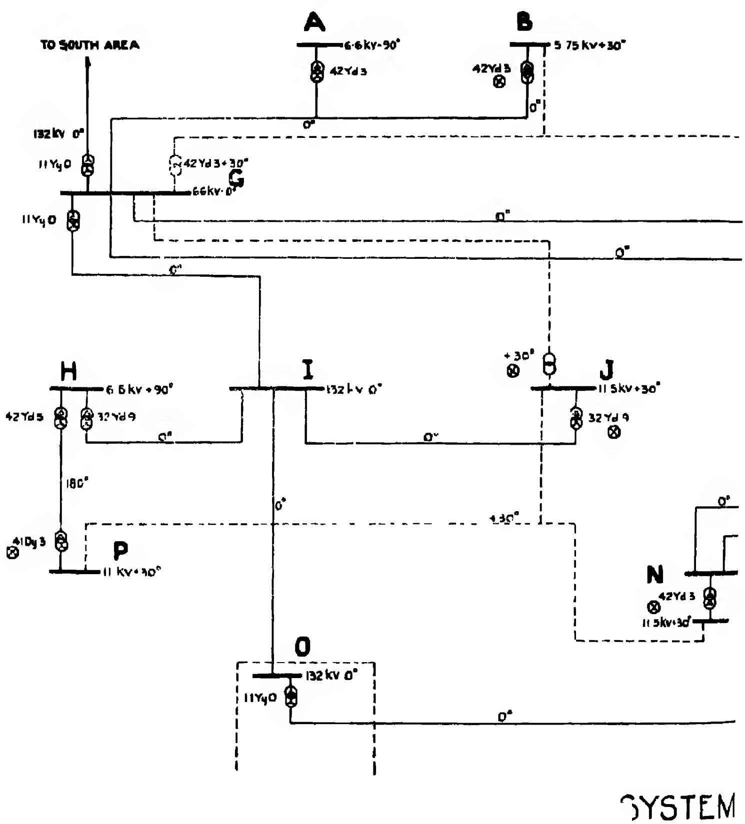
(3) Shut-down due to fault on plant in sub-station.

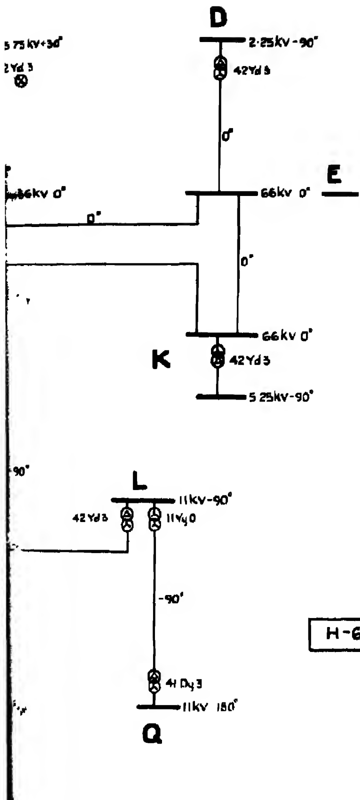
When conditions are normal, notify system control of all switching operations and load conditions.

Clocks. All recorders, time switches, or other clocks which require winding once weekly, must be wound up by the attendant every Thursday. Should the sub-station be attended morning and evening, the morning shift attendant shall be responsible. All clocks and recorders are to be checked daily with the power station master clock, and a note of any correction made is to be indicated on the chart and log book.

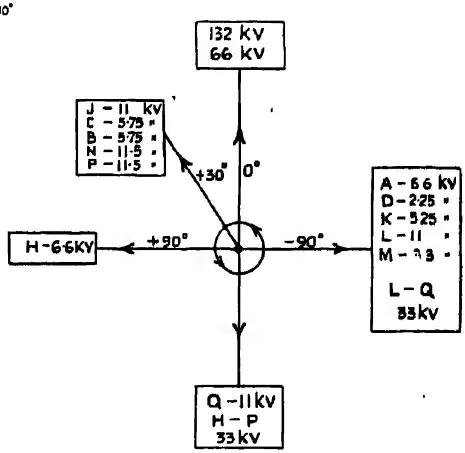
Attendance. Attendants must ring system control and have the times recorded when commencing and finishing duty. On leaving one sub-station and entering another, the sub-station attendants must advise system control. The attendant in charge must communicate with system control every two hours irrespective of whether the sub-station plant is running or not. Any attendant unable to take his shift should notify system control room at least two hours before the time such shift is due to commence.

Should any attendant not have been relieved within half an hour


TO SOUTH AREA
A
6·6 kV-90°
42 Yd 3
B
5 75 kV+30°
42 Yd 3
0°
132 kV 0°
11 Yy 0
42 Yd 3+30°
G
66 kV 0°
11 Yy 0
0°
H
6 6 kV +90°
42 Yd 5
32 Yd 9
I
132 kV 0°
+30°
J
11 5 kV+30°
32 Yd 9
180°
41 Dy 3
P
11 kV+30°
+30°
N
42 Yd 3
11 5 kV+30°
O
132 kV 0°
11 Yy 0
SYSTEM


D
2·25kv -90°
42Yd 3
0°
E
66kv 0°
0°
0°
66kv 0°
K
42Yd 3
5 25kv-90°
L
11kv-90°
42Yd 3
11Yy0
-90°
41 Dy 3
11kv 180°
Q

ASE DIAGRAM.


132 kV
66 kV
J - 11 kV
C - 5·75 "
B - 5·75 "
N - 11·5 "
P - 11·5 "
+30°
0°
H -6·6KV
+90°
-90°
A - 66 kV
D - 2·25 "
K - 5·25 "
L - 11 "
L - Q
33kV
Q - 11kV
H - P
33kV

after his normal shift ended, he must notify the system control engineer. Attendants must not change shifts without previous sanction.

On Leaving a Sub-station. The attendant must see to the following :

(*a*) Look round generally and see that all feeder, transformer, rectifier, and convertor switches are normal.

(*b*) Plug branch telephone line through to system control room.

(*c*) Switch off telephone extension bells.

(*d*) See that switch for remote signalling equipment is in " ON " position.

(*e*) See that all sub-station and transformer-room doors and gates are secured.

(*f*) Switch off all lights except one just at entrance.

On Entering Sub-station. (*a*) Switch on telephone extension bell and withdraw branch line plug.

(*b*) Note any remarks on log book and log sheet.

(*c*) Look round generally and see that all feeders which should be closed are closed.

(*d*) Run up plant as required.

Switching Operations after Fault Conditions. Before reclosing any feeder circuit breakers which have opened under fault conditions, it is extremely important that all persons immediately concerned should ascertain :

(*a*) the severity of the fault ;

(*b*) what tripping of switches has occurred at any points on the system ; and

(*c*) whether an earth fault has been indicated at the power station. With the above information in mind, reclosing of feeder circuit breakers should be carried out as follows :

(1) *Feeder Tripping on Earth Leakage Protection.* Reclose feeder circuit breaker TWICE. If the circuit breaker fails to remain closed leave the feeder out for the attention of the mains department.

(2) *Feeder Tripping on Overcurrent.* Reduce time setting on overcurrent relay to the minimum and reclose feeder circuit breaker ONCE. If the circuit breaker fails to remain closed, leave the feeder out for the attention of the mains department. If the circuit breaker remains closed, the time setting on the overcurrent relay should be put back to normal.

(3) *Feeder Tripping on Discriminating Protection* (*e.g.*, Beard-Hunter, Merz-Price, Split-Conductor, or Split-Pilot). Before closing the circuit breaker at one end, the operator should ascertain whether

the circuit breaker at the remote end of the protected section has also tripped. If it has tripped, the circuit breaker should not be reclosed until the mains department has approved. If the circuit breaker at the remote end of the protected section has not tripped, the operator can close the circuit breaker, but if the circuit breaker trips immediately, the feeder should be left out for the attention of the mains department.

Note. It is important that the mains department be accurately informed as to which circuit breakers have opened and the sequence, and, if possible, the cause of their opening, together with information as to whether or not any earth fault has been indicated.

The mains department should ascertain the severity of the fault that caused the circuit breakers to open, with a view to deciding the safety or otherwise of having any switch reclosed before the faulty plant has been isolated from the system. It may be advisable to sectionalise the system.

33 *kV. System.*

Transformer, Feeder } tripping on discriminating protection, *e.g.*, translay.

Reclosing should only be done after the mains department is satisfied that the cable or transformer is not faulty.

Transformer, Feeder } tripping on overcurrent protection.

Reclosing should only be done when it is clear that no fault exists.

Bus-zone Protective Gear Trip. No reclosing should be done until the cause of this trip has been found ; to resume supply, the feeders, etc., should be changed over to the other set of busbars, and made alive separately.

H.V. Regulations Relating to Sub-stations and Mains.

(1) No cubicle doors are to be opened, transformer lids removed, nor any work carried out in any sub-station, on any mains, or on any part of the H.V. supply system, without explicit instructions from the engineer in immediate charge of the work.

(2) Before any work is commenced on any part of the H.V. supply system, the engineer in immediate charge of the work must satisfy himself that all points at which connection with live gear is possible are disconnected from the supply and locked out. He must take charge of all the keys controlling access to the said points of connection, and none of the keys so obtained are to be released except on

the written authority of the engineer in immediate charge of the work at its completion.

All communications on these matters are to be made in writing on the forms provided.

(3) Before work is commenced, the circuit must be discharged by earthing with the earthing apparatus provided.

(4) The act of returning or replacing the controlling keys is to be taken as a guarantee that the work has been completed, and immediately the keys have been released the circuit is to be regarded as being alive.

(5) No work other than mere inspection is to be carried out in any sub-station in which is installed live plant or connections, unless under specific instructions, and unless accompanied by another person.

(6) In addition to the foregoing, the following regulations are to be observed for overhead lines and pole-mounted sub-stations, unless or until the circuit has been cleared in the manner laid down in Regulation 2 :

(*a*) A fallen wire must not be touched.

(*b*) No ladder must be placed in contact with any wires.

(*c*) No poles are to be climbed to a greater height than 10 ft. from the ground.

Inspection of Sub-stations. The following rules are to be implicitly obeyed by sub-station attendants and others when visiting such stations:

(1) No unauthorised person will be allowed in any sub-station.

(2) In the case of underground sub-stations, the access door must be closed or the gate lowered. The attendant must plug the telephone in, and, on leaving, switch off the lights, remove the telephone plug, lock gate or door, and replace manhole covers.

In the case of overground sub-stations, the attendant must see that the door is securely locked when leaving, in addition to the foregoing where applicable.

(3) Rubber gloves and mats or insulating stands are provided, and anyone neglecting to take the precaution of using these when working on or near a live man, or live metal, renders himself liable to dismissal.

(4) The sub-station attendants will be held responsible for the condition of rubber gloves, as well as for all the tools, fuses, etc., that may form part of the equipment, as shown on the list posted in each sub-station. It is their duty to see that all the articles on this

list are in their place and that the rubber gloves are in good condition. The gloves should be examined each time the station is visited and, if faulty, exchanged for new ones immediately any defect is discovered.

(5) The attendant is to report by telephone to the system control room on entering and leaving any sub-station ; he is also to report, immediately, all breakages or defects in any of the apparatus. Daily log sheets recording visits are to be handed to the system control room each evening.

(3) The attendant is to report to the system control room any circuit he finds shut down when in the sub-station, *but under no circumstances whatever is he to make the circuit alive.*

(7) The attendant must see that the sub-station is kept thoroughly clean and tidy, and inspect the M.V. switches and fuses, cleaning them when necessary, taking care to make use of the rubber gloves and mat when in close proximity to either the H.V. or M.V. circuits.

(8) Before any work is carried out on any part of the H.V. system, the H.V. regulations in connection with mains and sub-stations are to be strictly observed.

(9) These regulations apply to all sub-stations, and to the inspection of the fuse pillars over or immediately outside the sub-stations.

Works Sub-stations. In one works containing a number of sub-stations (each 2–500 kVA, 3·7 kV/410 V transformers) these are visited twice a day, when log sheets giving power factor, load, maximum demand and energy meter readings are completed. The earth leakage recorders in each sub-station are also examined. These recorders consist of a recording ammeter connected in the earth lead at the sub-station and thus show any earth faults occurring on the sections fed from that particular sub-station. From this information earths not cleared by fuses may be looked for and cleared. To protect the recording ammeter a relay is included in the earth circuit which shorts out the ammeter if the earth leakage current exceeds 40A. At the same time a series resistance is inserted in the earth lead to prevent further rise of current.

Electricity Supply Department Regulations. Rules to be observed by all persons requiring to work on H.V. switchgear and cables, in order to ensure the proper carrying out of Regulation 28 of the Electricity Regulations issued under the Factory and Workshop Acts, 1901–1911.

Regulation 28 reads as follows :

" No person, except an authorised person, or a competent person

acting under his immediate supervision, shall undertake any work where technical knowledge or experience is required, in order adequately to avoid danger ; and no person shall work alone in which the Secretary of State directs that he shall not.

" No person, except an authorised person, or a competent person over 21 years of age, acting under his immediate supervision, shall undertake any repair, alteration, extension, cleaning, or such work where technical knowledge or experience is required in order to avoid danger, and no person shall do such work unaccompanied."

(1) *Responsibility of Officer in Charge.* It must be clearly understood that the officer in charge of a power station, sub-station, H.V. cables or H.V. switchgear, who must be an " Authorised Person ", is responsible for the proper carrying out of these rules.

(2) " *Authorised Persons.*" Authorised persons, as defined in the above-mentioned regulations are :

> Electrical Engineer ; Deputy Electrical Engineer ; Mains and Sub-stations Engineers ; H.V. Mains Inspectors ; Power Station Superintendent ; Charge Engineers ; Junior Charge Engineers ; and others as deemed necessary.

(3) *Officer in Charge to be Informed.* If it is necessary for any man, whether in the employ of the authority or of any contractor, to work on any higher voltage switchgear, alternators, cables or plant at the power station or sub-stations, before commencing work he must report the matter to the officer in charge of the plant on duty at the time, who will decide whether it is necessary to isolate it.

(4) *Method to be Adopted for Isolating.* If isolation is necessary, the officer in charge, who must be an " Authorised Person ", must himself carry out the isolation in the presence of the man who proposes to work on the apparatus, and must show him that the isolating switches are open and the cubicle locked off. He must then deposit the keys in a receptacle provided for the purpose, lock this, and hand the keys to the man who proposes to work on the apparatus. Failing the provision of special receptacles, the keys of the cubicle itself are to be handed over to the man who proposes to work on the apparatus.

(5) *Both Ends to be Isolated.* Where a higher voltage cable or switch panel, which can be made alive from both ends, is to be worked on, the man in charge of the work must follow the procedure set out in (4) and obtain the keys controlling the cubicle concerned.

(6) *Safeguarding the Keys.* The keys so obtained must be kept in the possession of the man at work on the plant, who will be held

responsible for their safe keeping, and they must on no account be given up by him until he has completed his work, and the plant is again ready for service. If more than one person is at work on the same plant, the keys must be kept in the possession of the leading hand in charge of the work.

(7) *Testing Apparatus to Ensure its being "Dead".* Before allowing any man to work upon any plant that has to be made "dead",

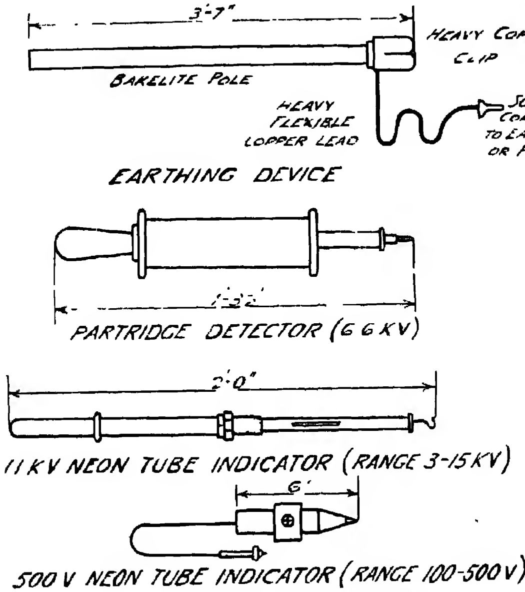


FIG. 326. Testing equipment.

the authorised person must test its condition by applying an insulated rod or condenser pole (Fig. 326) to the bare conductor before "*earthing*" same to satisfy himself that it is discharged.

(8) *Return of Keys.* After the work is completed, whoever has charge of the keys must satisfy himself that everything is clear and the plant that has been made "dead" is again ready for service. He must then report this to the officer in charge on duty at the time, before he returns the keys to such officer.

(9) *Responsibility for Isolation.* The above rules are to be strictly observed whether the work to be done is supposed to be dangerous or not, and the responsibility of deciding whether the work is sufficiently

dangerous to necessitate isolation of the plant will rest entirely with the officer in charge on duty at the time.

SAFETY AND OPERATION REGULATIONS

(1) General. All operations, work and maintenance on the system shall be carried out to comply with the following statutory requirements :

(*a*) Electricity Regulations (Form 954) ; and Explanatory Memorandum (Form 928).	Issued by the Home Office under the Factory and Workshop Act.
(*b*) Electricity (Supply) Regulations, 1937.	As made by the Electricity Commissioners for securing the safety of the public and ensuring a proper and sufficient supply of electrical energy.

The following regulations must also be observed where applicable :

(*c*) Workmen's Compensation Acts.

(*d*) Overhead Line Regulations (Form El.C. 53).

(*e*) Regulations for Tramways as made by the Minister of Transport.

(*f*) Mining Regulations issued under the Coal Mines Act.

(*g*) Regulations for the Electrical Equipment of Buildings (I.E.E.).

(2) Authorised Persons. A list will be maintained by the head of each department giving the names of all persons deputed to act as " Authorised Persons " within the meaning of the Acts. Such persons will be supplied, on request, with a copy of the regulations mentioned above and must make themselves familiar with them.

The list will define which of the " Authorised Persons " are deputed to carry out or supervise switching operations.

(3) Competent Persons. A competent person is defined as a person over 21 years of age with sufficient knowledge and/or skill to avoid danger. No person except an authorised person or a competent person acting under his immediate supervision shall undertake work when danger is involved in accordance with Regulation 28 of Form 954 referred to.

In the event of non-competent persons being required to do work in sub-stations, etc., such as painting or building work, they must be under the direct personal supervision of a competent person, who must be present the entire time, and who must be responsible for

seeing that the work is carried out to avoid danger to persons and damage to plant.

(4) **Accidents.** In the event of any accident to an employee or any dangerous occurrence, particulars must be reported to the system control engineer with the least possible delay, preferably by telephone, and followed up by a written report.

(5) **Sub-stations Department—Equipment.** The following items must be kept and maintained in good condition in all sub-stations :

(*a*) A copy of the Electricity Regulations, Form 954.
(*b*) A card of Instructions for Treatment of Electric Shock.
(*c*) Log Sheet, on board (for recording all visits and switching, etc.).

In addition, the more important sub-stations must be furnished with the following items :

(*d*) First aid outfit.
(*e*) Rubber gloves.
(*f*) Rubber mat(s).
(*g*) Buckets of sand, or fire extinguishers.
(*h*) Hand lamp (H.O. pattern) with plug and flexible lead long enough to reach every part of the sub-station.
(*i*) Emergency portable electric hand lamp.
(*j*) Metal plates, or labels marked " Danger ".

In the switchhouses at the power stations, in outdoor sub-stations, and in the smaller indoor sub-stations where it is not practicable to have all the items listed above, a notice must be placed in a conspicuous position stating the nearest sub-station in the vicinity where such items can be obtained quickly.

(6) **Work on Higher Voltage Equipment.** Where it is necessary to work on cables, switchgear, or transformers, etc., normally alive at higher voltage, the authorised person deputed to carry out switching operations will be responsible for such apparatus being switched out, isolated, earthed and locked off, and danger notices being affixed ; and for making any other arrangements necessary to enable the work to be carried out in safety.

(7) **"Permit-to-Work" Cards.** No person may start work on higher voltage equipment unless he is in possession of an official " Permit-to-Work " card, or has seen and signed such a " Permit-to-Work " card. A typical card is given. Books of these cards will be provided for each authorised person deputed to carry out switching operations, by whom the permits will be signed and issued.

Typical "Permit-to-Work" Card

CITY OF . . ELECTRICITY DEPARTMENT
PERMIT TO WORK ON ELECTRICAL APPARATUS

Person to whom this permit is issued

It is safe to work $\frac{\text{IN}}{\text{ON}}$ the following $\frac{\text{LOCATION}}{\text{APPARATUS}}$ under the supervision of

Here state the nature and extent of the work covered by this permit

Here state exactly the $\frac{\text{LOCATION}}{\text{APPARATUS}}$

$\frac{\text{IN}}{\text{ON}}$ which it is safe to work

The above apparatus is / has: Dead; Earthed at; Danger Notice posted; Control Fuses removed — Strike out the words which do not apply

When a Supervisor is provided other than the person to whom this permit is issued, this permit becomes invalid in the absence of that Supervisor
CO_2 GAS suppressed—YES/NO

DECLARATION BY ENGINEER-IN-CHARGE .

I have satisfied myself that the $\frac{\text{LOCATION}}{\text{APPARATUS}}$ stated above is safe to work $\frac{\text{IN}}{\text{UPON}}$ and that the work is adequately supervised.

Signed	Shift Engineer.		Date Issued / Date Renewed		Time
,,	,,	,,			,
,,	,,	,,	,,	,	
,,	,,	,,	,,	,,	,,
,,	,,	,,	,,	,,	,,
,,	,,	,,	,,	,,	,,

RECEIVED by

on	on
on	on
on	on

CLEARANCE

I hereby declare that all men under my charge have been withdrawn and warned that it is no longer safe to work $\frac{\text{IN}}{\text{ON}}$ the above $\frac{\text{LOCATION}}{\text{APPARATUS}}$ and that all tools and gear have been removed, leaving the apparatus ready for putting into commission.

Signed by Date Time

CANCELLATION

I have inspected the $\frac{\text{LOCATION}}{\text{APPARATUS}}$ covered by the above clearance and I am satisfied that it is fit to go into commission I have removed all Earths , the apparatus has been tested for Earths, and is now in commission

Signed by Date Time

The " Permit-to-Work " will normally be issued to the engineer in charge of the work. He will then write on the back of the permit the names of the jointers or other competent persons engaged on the work, and obtain the signatures of these persons both before any work is started, and after it has been completed.

In cases where only one competent person is involved on the work, the permit may, with the consent of the engineer in charge of the work, be issued direct to that competent person.

In all cases, the keys controlling the equipment concerned must be handed over to the official in charge, along with the " Permit-to-Work ", and neither the keys, nor the permit, is to be taken away, but must be retained on the job until the work is completed.

(8) **Clearance Certificates.** On completion of any work for which a " Permit-to-Work " has been issued, the official in charge of the work, *after ascertaining* :

(*a*) that all workmen are clear of the apparatus,

and

(*b*) that the apparatus is safe and ready to be put into commission,

will sign the " Clearance Certificate " at the foot of the " Permit-to-Work " card, and return the card to the authorised person deputed to carry out switching operations. As far as possible, each card should be returned to the particular authorised person to whom the certificate was issued.

This authorised person, *after satisfying himself* that the apparatus is ready, will cancel the " Permit-to-Work " card, remove the earth connections, and switch the apparatus into commission, as required. Responsibility will rest entirely upon any switching operator, at all times, for seeing that he holds a clearance certificate where necessary to cover every switching operation. This applies equally to new equipment which is being put into commission for the first time, in which case the operator shall obtain a suitable clearance certificate from the engineer in charge of the jointing or erection section, etc. Where switching operations involve persons or equipment outside the department, *i.e.*, contractors' staffs or consumers' representatives, the procedure of written " Permit-to-Work " cards and " Clearance Certificates " shall be strictly observed.

(9) **Responsibility for Switching on Supply System.** All switching on system will normally be directed by the system control engineer, and carried out only by the regular operation staff. The actual

operation of opening or closing a switch must be carried out by the operator himself, and he must always be accompanied by at least one other competent person.

The system control engineer must always be notified prior to any routine switching on the mains affecting feeder loadings. This is also particularly important when fault conditions are being dealt with, but if it is impracticable to get into touch with the system control room beforehand, care must be taken to confirm the situation (by telephone) as soon as possible afterwards.

When switching is being carried out between different sections of the network, care must be taken to ascertain that the power stations are in parallel, and that the load and voltage conditions are suitable.

All switching operations in sub-stations shall be recorded on " Switching Record Notes " provided for this purpose. Each operator will carry one of these books with him, and will make an entry immediately after each operation, taking care to note the time accurately. As soon as possible thereafter, the record shall be returned to the office, and initialled by the system control engineer before being filed. This will ensure that all relevant parties are kept informed of all switching changes. The sub-station switching log book kept in the operation section will be entered up promptly on receipt of each switching record note, so that all operators can verify the position by inspection of the log book.

The serial number of each " Permit-to-Work " card issued must be cross-referenced on the relevant " Switching Record Note ", and this number shall be entered in red ink with appropriate particulars in the log book, so that all operators will know what " Permits-to-Work " are outstanding. A similar entry in red ink shall be repeated on each change of shift for as long as any permit remains uncancelled.

The cancelled " Permit-to-Work " cards will be filed, after inspection, by the system control engineer.

(10) Earthing. Before issuing any " Permit-to-Work " card, the authorised person deputed to carry out switching operations *will be responsible* for seeing that an efficient earth is placed on the circuit concerned. Suitable earthing equipment will be provided for this purpose, where practicable, to fit every type of switch on the system, and shall be kept readily available by the operation staff. Where possible, the lock-up arrangements should definitely lock the earthing connections in position.

Irrespective of this precaution, it shall be a personal responsibility

jointly on the part of the competent person detailed to carry out the work and of the official in charge, to earth the parts of the circuit concerned wherever practicable as close as possible to the " point of work ".

All such earths shall be kept in position as far as practicable until the work has been completed.

Before cutting into any cable, jointers shall take care to drive a spike with insulated handle through the lead of the cable into the cores, and during this operation rubber gloves must be worn on both hands. Where more than one cable is present in a pit, or track, very special care is needed to find the correct cable. Where this cannot be done by tracing back to switchgear, a positive check shall be made wherever possible by opening a small piece of lead to expose the test sheath, and taking megger tests with the sheath first earthed and then opened.

Before working on any overhead line, the conductors shall be securely earthed by throwing over them a light metal chain with one end connected to earth.

(11) Padlocks and Keys. A set of numbered padlocks will be specially provided for locking off switches, and these locks will be all different, that is to say, the key of one padlock will not unlock any of the others.

Two keys for each padlock shall be provided, one to be the key for normal use and the other to be a spare key. The key for normal use shall have securely attached to it a round brass label with the number of the padlock boldly stamped on it. The spare key shall have securely attached to it a square brass label, also boldly stamped with the number of the padlock.

The padlocks for mains department work, together with the normal keys, will be kept on hooks in a cabinet to be installed in the sub-station operation section.

Separate and distinctive sets of padlocks will be used at each power station, for use on the switchgear in the station. In these cases the padlocks and normal keys will be kept in a cabinet in the control room, accessible only to the shift charge engineers.

The spare keys must be locked up in the possession of the system control engineer, and these must not be used except in emergency, and in this event the system control engineer will be responsible.

The numerals 6 and 9 should not be used alone or in combination in circumstances which might lead to confusion.

(12) Screening of Busbars, etc. On metal-clad gear, each busbar safety shutter should be stencilled " BUSBAR ". Where more than one busbar exists, each set should be clearly distinguished.

Whenever a switch is isolated, the busbar shutters must be padlocked in the shut position, and this must be done at once before any further action is taken such as the earthing of the feeder sockets.

(13) Remote Controlled Gear. Whilst work is carried out on remote controlled gear such as power station switchgear and transformer tap-changing gear, or on cranes, the authorised person deputed for switching operation is responsible for removing all fuses from the control and tripping circuits, and for seeing that the mechanism is blocked where necessary to prevent accidents of a mechanical nature.

(14) Crane Wires. In the case of crane wires, or in other cases where the men may be working in a dangerous position, involving the possibility of a fall in the event of shock from leakage current, special care must be taken, and the crane wires or other metal must be efficiently earthed ; generally all cases of this kind should be treated as " H.V. ".

(15) Rubber Gloves. Every competent person's kit must include a pair of rubber gloves, and the competent person is personally responsible for keeping these in good condition, and for having the gloves replaced when necessary. Every switching operator shall also carry a pair of such gloves with him whenever on duty. Gloves kept in the more important sub-stations shall be stored in metal boxes filled with french chalk, and the gloves shall be replaced and brought in for testing about once a year. Gloves brought in shall be inspected and tested before being re-issued for further use.

(16) Sub-station Log Sheets. A log sheet clipped to a board will be kept in each sub-station, and all persons entering the sub-station are required to enter the date and time on such sheet, together with brief particulars of the reason for each visit. Any switching operations are to be recorded on the log sheets. The log sheets are to be renewed every six months, or oftener if necessary, the completed sheets being sent to the system control room for inspection before filing.

(17) Interconnections. In numerous cases H.V. sub-stations are, or may be, interconnected through the low tension networks. Switching operators need to exercise great care to ensure that any equipment is not inadvertently kept " alive " through such interconnections.

A further risk arises of heavy circulating currents on cables inter-

connecting networks fed from different power stations or higher voltage primary sub-stations. Precautionary labels shall be fixed at all points where such interconnections can possibly take place.

(18) General—Lower Voltages. The maintenance and operation of low and medium pressure mains and apparatus shall be carried out strictly in accordance with the foregoing regulations, subject to the following clauses. It should be noted that the underlying principle shall be strictly adhered to : that wherever there is danger the competent person engaged in the work shall always be guided by the "Authorised Person" who is responsible.

(19) Work on Live Conductors. Where it is necessary to work on live apparatus to avoid interrupting the supply, such work shall be carried out only by men accustomed to working under such conditions and properly equipped to avoid danger.

In any case where the person detailed to carry out such work is not confident of carrying it out safely, he shall not commence the work but shall notify the official in charge, who shall then be responsible for making suitable arrangements to enable the work to be proceeded with without danger.

The engineer in charge shall be responsible for seeing that each man is provided with *and uses* rubber gloves, boots, mats and insulated tools as may be considered advisable to avoid danger.

At least two persons shall be present whenever work is being carried out on live conductors.

(20) Work on Dead Conductors. Lower voltage conductors and apparatus must always be assumed to be "alive" unless the official in charge of the work is in possession of a "Permit-to-Work" stating that such apparatus has been made dead. Verbal information on such matters must never be accepted.

"Permits-to-Work" will be issued only by authorised persons deputed to carry out operations, who shall be responsible for opening the switch or removing the fuses and securely affixing "Danger" notices to the switches or fuse-ways controlling the circuit concerned. If it is not possible to lock-off fuse-ways and/or to earth the circuit, care should be taken suitably to amend the information given on the "Permit-to-Work".

Whenever work is to be carried out on dead conductors, the competent person doing the work shall satisfy himself that the conductors are dead by testing with a lamp, voltmeter, or other reasonable means, and he shall himself affix an earth wire at the point of work wherever

possible. He shall also satisfy himself that the circuit cannot be made alive without notice being given to him.

(21) Work on Overhead Lines. Make sure the ladders are in sound condition. As soon as a ladder has been placed against the pole the top must be securely fastened with a piece of rope. Every man working above ground must wear a safety belt. Before proceeding to do any work on a line the linesman is personally responsible for satisfying himself whether the line is dead or alive, irrespective of any assurance he may have received from other people. Whilst working on a dead line, a bonding chain must be wrapped on to all conductors. Where work on live mains is unavoidable, rubber gloves and boots must be worn, and two persons must be present. When completing live service connections a rubber mat shall be used as a screen between conductors.

PLANT COMMISSIONING, INSPECTION AND MAINTENANCE

The commissioning of sub-station plant varies according to the types installed, but generally falls into the following sections :

Switchgear. Insulation tests are necessary with a 2·5 kV Megger before and after voltage tests ; I.R. tests should also be taken of all current and voltage transformers ; voltage tests ; oil tests ; operation —closing and tripping at the limits of permitted battery voltage ; measurement of circuit breaker pre-arcing tripping times ; primary current injection tests to check ratio of instrument current transformers and calibration of instruments.

Transformers. Insulation tests with 2·5 kV Megger ; phasing out ; dielectric strength and acidity of oil samples ; operation of tap-changing equipment, and voltage regulating relay, if fitted ; operation of cooling equipment, control gear, and temperature alarms.

Rectifiers. Phasing out ; insulation tests ; voltage across anodes and between anodes and neutral point ; operation of auxiliaries and protective circuits.

Convertors. Insulation tests ; phasing out ; running up and operation of auxiliaries and control gear.

Protective Equipment. Insulation tests of pilots and circuits ; primary injection tests to check current transformer ratio ; stability and operation under service conditions ; secondary injection tests to check calibration of relays at varying settings ; Buchholz relays and

associated apparatus to be tested ; 50 per cent. rated voltage test on D.C. operated relays.

Feeders. Insulation tests, 2·5 kV Megger ; D.C. voltage tests, etc.

As a guide and reminder to the operating and maintenance staffs concerned in keeping sub-station equipment in good order, it is advisable to draw up a schedule setting out the periods recommended between inspections, and the items requiring attention. For static transforming stations, monthly inspections are usually sufficient, and would include tests on tripping battery ; transformer and circuit breaker replacements as and when required ; replacement of overheated main and time limit fuses ; measurement of earth leakage current on the lower voltage network ; recording of transformer loadings and corresponding temperatures, etc.

In so far as the individual items of plant are concerned the following are worthy of attention :

Transformers. Oil samples annually : checking oil gauges, temperature indicators, cooling equipment and valves : cleaning insulators, inspection and cleaning of tap-changing equipment, etc.

Switchgear. Oil samples annually ; inspection of mechanism, contacts and connections ; cleaning of bushings, etc. ; hand operation of all circuit breakers—tripping by relay and closing by hand or spring-closing device should be carried out, say, once every six months. The tripping circuit auxiliary switches can be tested before replacing the tanks—a dry battery and bell circuit being suitable—to ensure that these are well in advance of the main arcing contacts, and that the trip circuit is maintained throughout the closing operation.

Converting Plant. General inspection and cleaning : windings blown out ; commutator and brushgear ; compressed air at a pressure of not exceeding 25 p.s.i. is suitable for blowing out armatures and brushgear. The skin on a commutator should never be destroyed unless the surface has become grooved or has been pitted due to flash-over. After re-surfacing by pumice stone, or grinding, a machine should be gradually loaded, say, from 20 per cent. to full load over a period of four days, to allow a good skin to be formed. Bearings and oil levels checked ; overspeed and other protective devices to be tested.

Rectifiers. General inspection and cleaning ; checking operation of auxiliary equipment ; check instruments, seals, thermostats, and protective devices.

Cables. Check loading ; clean manholes ; check cable boxes, connections, earthing bonds, etc.

Protective Equipment. Tripping battery inspection and testing; renewing of time limit fuses, especially where load fluctuations are pronounced; temperature variations, which occur during load cycle, result in molecular crystallisation which tends to reduce the fusing current and ultimately fracture the fuse element. It is usually difficult to detect such failures with a Galvo. or Megger. Periodical replacement on a rota system is desirable. The conductivity of all earth connections should be measured and recorded. A simple test is by connecting one lead of an A.C. supply to one terminal of earth plate and the other lead to a water main (if at hand), and from the voltmeter and ammeter readings obtained the approximate resistance can be estimated. The "Meg" earth tester may also be used.

Bibliography

I. M. E. AITKEN. "Remote Indication by a Wheatstone Bridge System," *Journal I.E.E.*, Vol. 94, Part II, No. 39, June, 1947.

A. BARBAGELATA. "Present-day Tendencies in the Regulation of Interconnected Central Stations and Systems," *Electrotecnia*, Vol. 25, 25th April, 1938.

G. A. BURNS and T. R. RAYNER. "Remote Control of Power Networks," *Journal I.E.E.*, Vol. 79, 1936.

T. H. CARR. "Power Station Control Rooms and their Equipment," *The Electrical Engineer*, 9th June, 1939.

" "Sub-station Organisation and System Control," *Distribution of Electricity*, October, 1945.

J. FALCKE. "Some Notes on the Centralised Control System, V.F. and T.V. Power Company," *South African I.E.E.*, 1930, Vol. 21.

F. JAGER. "Joint Operation of Remote Control in Automatic Installations," *V.D.E. Fachberichte*, Vol. 9.

W. KIDD and E. M. S. MCWHIRTER. "Operational Control of Electricity Supply Systems," *Journal I.E.E.*, Vol. 92, Part No. 28, 1945.

W. KIDD and J. L. CARR. "The Applications of Automatic Voltage and Switch Control to Electrical Distribution Systems," *Journal I.E.E.*, Vol. 74, 1934.

Y. LE MOIGNE and M. TARON. "Despatching in the Parisian Company for the Distribution of Electricity," *R.G.E.*, Vol. 43, 21st May, 1938.

J. D. PEATTIE. "Control Rooms and Control Equipment of the Grid," *Journal I.E.E.*, Vol. 81, 1937.

H. RISSIK. "Power System Interconnection." (Pitman.)

G. F. SHOTTER and E. E. HUTCHINGS. "Potential Indicators for Live Conductor Tester," *E.R.A. Tech. Report*, F/T133.

E. G. SWANGREN. "Load Distribution and Control of Large High Voltage Interconnected Systems," *Mining Electrical Engineer*, January, 1937.

H. P. YOUNG. "Electric Power System Control." (Chapman & Hall.)

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